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Large Bolted Connections

CALIBRATION OF ALLOY STEEL BOLTS

by

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Professor in Charge

Head of the Department

A C K N O W L E D G E M E N T S

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A B S T R A C T

Presented herein are the results of the tensile calibration of individual ASTM A354 BC, A354 BD, and A490 quenched and tempered alloy steel bolts. All bolts tested were of either 7/8 inch or 1 inch nominal diameter. Results of 84 direct tensile tests and 146 wrench-induced tensile tests are discussed as well as the results of 39 machined coupon tests and a number of special tensile tests. Wrench-installed bolts are said to have attained a torque induced tension or, more commonly, torqued tension. Major variables studied were method of inducing tension, bolt diameter, grip, thread in grip, and thread lubrication. Both regular semi-finished hexagon head and heavy semi-finished hexagon head bolts were tested.

The special tensile tests dealt with the effects of direct tensile loads on wrench-installed bolts, repeated wrench installation of bolts, wrench installation of bolts gripping steel plate rather than a hydraulic load cell, and continuous rather than incremental installation of bolts with an impact wrench.

The purpose of this series of tests was to investigate the tensile behavior of the alloy steel bolt so that it could safely join the A325 bolt for use as a structural fastener. The conclusions drawn from these tests have been written with this in mind.

From all indications the alloy steel bolt is indeed suited to structural use and can fill the growing need for a fastener to be used with the high strength steels in use today.

1. INTRODUCTION

1.1 PURPOSE

The prime objective of this study is the investigation of the behavior and performance of the alloy steel structural bolt when subjected to various conditions of installation and service load. A knowledge of this behavior and performance is required to determine the applicability and limitations of this bolt for use as a structural fastener.

Knowledge of the tensile behavior of a bolt is important for the following reasons. First of all, this behavior affects required installation practices and methods of inspection. Secondly, where a joint is designed to resist forces by bolt tension, information is needed to predict the deformation and load capacities of the connection. Finally, in a friction-type joint the available frictional resistance before the joint slips into bearing is directly controlled by the tension in the bolts. For these reasons, relationships must be established to predict the tensile behavior of a bolt loaded either directly or by wrench or by a combination of the two.

In addition to the primary questions of basic tensile behavior, several other problems deserve attention. How will an alloy steel bolt installed with a wrench react to directly applied tensile forces? How often can these bolts be reinstalled? Is the relationship between nut rotation and bolt load changed substantially when the bolt is installed in an actual joint rather than in a hydraulic load cell. Do these bolts react any differently when tightened continuously to a given load or rotation than when tightened incrementally as most experimental procedures require?

These, then are the problems that will be discussed in this report.

1.2 TEST PROGRAM

The test program included the study of the tensile behavior of eight lots of bolts conforming to ASTM designation A354-58T, grades BC and BD[1], and eight lots conforming to the A490[2] specification for quenched and tempered alloy steel structural bolts. The A490 specification calls for the heavy head and short thread length of the A325[3] specification and lists the chemical and physical characteristics of the A354 grade BD bolt. Its behavior would therefore be expected to be nearly identical to that of the A354 BD bolt. Bolt lots AD, BD, CD, and DD were made to conform to the A490 specification by re-heat treating Canadian bolts manufactured to AISI specification 4140.

Both heavy and regular semi-finished hexagon bolts were tested as were bolts with diameters of 7/8 and 1 inch. ASTM A194[4] grade 2H nuts with heavy semi-finished hexagon heads were used with all bolts tested. Hardened washers were used under all nuts. All reference to bolt head and nut size is that which is defined in the American Standards Association specification B18.2[5].

Table 1 describes the test specimens, including such variables as length under head (L), grip length (g), thread length under nut (t), diameter, head size, and type of thread. Each lot is designated by two letters followed by a series of numbers and letters. The first number following the double letters indicates the bolt diameter in eighths of an inch. The next number or numbers indicates the length of thread under the nut in sixteenths of an inch. Finally, the letter S or L at the end of the designation differentiates between short (approx. 4 inches) and long (approx. 8 inches) grip lengths. For example, the designation AC-7-9S indicates a 7/8 inch diameter bolt with 9/16 inch thread under the nut and a short grip length.

Since the A490 specification was not yet published at the time these tests were initiated and since the A354 bolt was not in general use as a structural fastener, all of the bolts used for this study were manufactured specially and because of this, exhibited a greater variation in properties, both geometric and structural, than would ordinarily be expected. Several problems were encountered because of this, including sub-standard thread fit for some lots, a wide scatter of individual test results and a complete lack of shipping oil on the A354 BC grade bolts. Special attention was given to the correction of these difficulties.

The overall testing program was planned to investigate the previously discussed major and secondary effects on the tensile behavior of these bolts. Bolt coupon and hardness tests were also conducted as a means of establishing trends based on the basic physical properties specified by ASTM. Table 2 lists ASTM specified properties in condensed form for the 7/8 and 1 inch diameter bolts. In addition to the properties called for in the A354 and the A490 specifications, the corresponding values from the A325 specification are listed for comparison. Although the A325 bolt is of a medium carbon steel and the A354 and A490 bolts are of an alloy steel, it can be seen that the A354 BC bolt has only a slightly higher tensile strength and hardness than the A325 bolt.

The complete testing program listing all bolt tests conducted except coupon and hardness tests, is shown in Table 3. The number of tests of each type is listed for every lot. In planning the program, emphasis was placed on the determination of basic tensile behavior in both direct and torque-induced tension. The torqued tension tests of the A354 BC bolts with threads "as received" were actually conducted with threads covered with a light, water soluble shipping oil which was applied after it had proven impossible to properly test tham in their true as-received condition (completely devoid of shipping oil. Before this oil was applied, threads seized with applied loads as low as ten kips.

Because of the critical behavior observed for bolts tested without shipping oil, a second series of torqued tension tests was conducted with a heavy multi purpose, grease type lubricant applied to the threads of both nut and bolt, to observe any effects of a lubricant heavier than shipping oil.

In addition to these basic tests, several special tests were conducted to investigate the problems discussed earlier. These tests are also indicated in Table 3. These special tests were all conducted without the use of a heavy lubricant. A description of the methods used and measurements taken for each type of test will be given in Chapter 2.

1.3 LITERATURE SURVEY

As early as 1934, the possible advantages of high strength bolts over rivets was recognized in Britain. Batho and Bateman[6] discussed the reduction of noise, the better slip resistance of joints, and the possible increased economy of high strength bolts as opposed to rivets. This discussion was included in a published report which also covered tensile tests of high tensile, heat treated carbon (0.40%) steel bolts with strengths nearly equal to those of the present A325 bolt. Much of the testing equipment and instrumentation used then was not far removed from that in use today. A recent report by Easton, Lewis and Wright[7] mentions a machine design text written in 1883 extolling the advantageous effects of high clamping forces on the fatigue strength of bolted joints.

Wilson and Thomas[8], are usually credited with encouraging the early development of high strength bolts in this country as a result of their fatigue tests in 1938. In 1947 Wilson became one of the organizers of the Research Council on Riveted and Bolted Structural Joints. This body has been responsible for much of the recent development of the high strength bolt as a structural fastener.

The first specification for the installation of high strength bolts in structural connections was published by the Research Council in 1951[9]. Subsequent specification were published in 1954[10], 1960[11], and 1962[12] incorporating the results of continued research and development. Through 1962, the A325 bolt was the only high strength bolt directly specified. In 1964, a new specification was approved[13] which included allowable stresses and installation procedures for the heat treated, alloy steel A490 bolt.

Quite a few reports have been written in recent years concerning the tensile calibration of A325 bolts[14][15][16][17]. Most of the conclusions of these reports show close general agreement. Reference 16 by Rumpf and Fisher discuss several other reports on high strength bolts, including those that were credited with the development of the turn-of-nut method of bolt installation. A report by Chesson and Munse[18] in 1962 was the first generally available report on the tensile calibration of A354 bolts including the BD grade, the predecessor of the A490 bolt. This report compared a limited number of tests of the A354 BC and BD bolts to tests of A325 bolts. More recently two reports have been written as a result of the cooperative study of the tensile calibration of A490 bolts conducted at Lehigh[19] and the University of Illinois[20]. Two lots of bolts were tested in various ways with the prime purpose of comparing the respective testing methods of the two institutions. The bolts which were tested at Lehigh as part of that study, have been included as a part of this report (lots LI and AB).

The behavior of alloy steel bolts in shear has been well documented by Wallaert and Fisher[21]. These shear tests were conducted for the same lots of bolts reported herein.

2. TEST PREPARATION AND PROCEDURE

2.1 PREPARATION OF BOLTS

Before testing, all bolts were stamped with their lot designations and with a number to identify them within their lot. Holes were then drilled with a combination drill and countersink in the center of each end of the bolt. These holes provided rings of contact for the tips of the C-frame extensometer at the interface of the drilled and countersunk portions. This type of contact was protected from damage and gave consistent readings which were insensitive to minor inclusion of dirt. Reference 14 gives a more detailed description of this preparation.

As previously stated, the A354 BC bolts were received completely devoid of shipping oil. When several bolts were tested in this condition the threads bound at extremely low loads and the nuts had to be burned off with a torch. Because of this, a light water soluble oil identical to that used by a major bolt manufacturer was applied to these bolts so that testing could be resumed. As a result of this experience, thread lubrication was included as one of the major variables to be studied.

Every bolt was checked for thread fit with the NC2A "Go" and "No-Go" ring gages, and each nut was similarly checked with the NC2B plug gages. Only those bolts and nuts with proper thread fit were used in the testing program.

2.2 TESTING EQUIPMENT

Bolt coupons were tested in a 60 kip hydraulic universal testing machine, using threaded tension grips to hold the coupons and a Peters extensometer to measure their elongation. The extensometer had a dial with divisions of 0.001 inch and a mechanical advantage of 5:1, giving accurate readings as small as 0.0002 inch.

A 300 kip universal hydraulic testing machine was used for the direct tension tests of full size bolts with special tension grips to hold the bolt under head and nut. Figure 1 shows these grips in the testing machine and also shows an extensometer in position to measure bolt elongations. The holes in the tension grips would accommodate a 1-1/8 inch diameter bolt with a 1/16 inch clearance. Fittings were provided so that either 7/8 or 1 inch bolts could be tested with the same clearance of 1/16 inch. In this way the bolt head and nut would not be stressed more severely than in an actual connection.

Two different hydraulic bolt calibrators were used to measure bolt tension during the torqued tension tests. One, with a capacity of 100 kips was used for the tests of 7/8 inch bolts[22]. The other, with a tensile capacity of 220 kips and a better resistance to torque, was used for all torqued tension tests of 1 inch diameter bolts. This calibrator is shown in Fig. 2 with a bolt ready for testing. Load is measured for both calibrators by the transfer of bolt tension through a hydraulic cell filled with a medium weight oil to a Bourdon pressure gage which is marked to read the total applied load in pounds. These calibrators were checked frequently for accuracy by loading them with a hydraulic testing machine of known precision. The resulting error was on the order of 2 kips low for each calibrator and did not depend on the magnitude of load nor its direction, increasing or decreasing. These errors remained constant during the testing period and were corrected as the raw data was taken.

The wrench used for all torqued tension tests was a large capacity pneumatic impact wrench running on a line pressure of approximately 30 psi. The wrench capacity was adequate for all bolts tested.

The small bolt calibrator when coupled to an oil pump, as shown in Fig. 3, was used to test the bolts in combined torqued-then-direct tension. The pump had an indicated capacity of 10,000 psi, which was more than adequate to reach the ultimate loads of these bolts when acting on the area of 28.86 sq. inches provided by the load cell of the bolt calibrator.

All bolt elongations were measured with the C-frame extensometer shown in Fig. 4, consisting of a rigid, adjustable steel frame and an Ames dial with divisions of 0.0001 inch. Rough adjustment was provided for by interchangeable straps of varying length which fasten to each of the arms. Fine adjustment was provided for by the threaded point opposite the dial gage. A counterweight was connected to the upper arm of the frame so that it balanced in the measuring position as shown in Fig. 1.

2.3 COUPON AND HARDNESS TESTING PROCEDURES

Coupon and hardness tests were conducted according to the applicable testing procedure specified in ASTM designation A370[23], specifically Supplement III. For coupons, it specified ½ inch round coupons with a gage length of twoinches, turned concentrically with the bolt axis from the shank portion of the bolt. More precisely, coupons of 0.505 inch diameter were used. The gage length was also reduced to 1.90 inches to allow readings in the initial inelastic range before the Peters gage reached the end of its travel.

These coupons were tested in the 60 kip testing machine at an indicated strain rage of approximately 0.02 inches per minute. A complete stress-strain curve was obtained for each coupon with particular emphasis on ultimate tensile strength, final elongation, and final reduction in area. The Peters gage was used to measure elongations in the elastic and initial plastic range and a steel scale and dividers were used for the remainder of the test. The final cross sectional area at the fracture was determined by using a micrometer to measure two mutually perpendicular diameters and using the mean value to calculate the equivalent circular area. Results are given in the next section.

Hardness tests were conducted according to the A370 specification on the sides of the bolt head. A belt gringer was used to remove all scale from the areas to be tested and to obtain a smoothly polished surface. Heat input was kept to a minimum by using water during the grinding operation. Standard Brinell and Rockwell C hardness tests were then conducted. Two trials were made on each bolt for each type of hardness test and at least two bolts from each lot were tested.

2.4 DIRECT TENSION TESTING PROCEDURE

All direct tension tests were conducted in the 300 kip hydraulic testing machine. Each bolt was installed in the tension grips as shown in Fig. 1 with the nut in the desired position. This position was determined by measuring the length of thread under the nut (shown as t in Table 1) from the bearing face of the nut to the last good thread on the bolt.

The initial bolt length was then measured with the C-frame extensometer with no load on the bolt and the extensometer was left on while load was applied. The bolt was loaded to its specified proof load and then the load was removed and the length was again measured to assure that no permanent set had occurred. ASTM specification A370 allows a variation between these readings of 0.0005 inch due to possible instrument error. If a larger variation was measured, the bolt was rejected as not meeting the specification. Of the 84 bolts tested in direct tension only three were rejected on this basis, and two of these were later found to have had microscopic cracks through their shanks at the base of the head, so that their effective area at that point was only about one half of the shank area.

After the bolt was checked in this manner it was again loaded, this time to failure. Load was applied at a rate of approximately 0.01 inch total elongation per minute. Loads and elongations were measured at 10 kip intervals in the elastic range and at 0.01 inch increments in the inelastic range until ultimate load was reached. Then, after one or two more readings, the extensometer was removed and the bolt was allowed to fail at the same rate of elongation. During the inelastic range of the test the machine was stopped one or more times to determine the static load level. This was consistently found to be about one kip below that at testing speed. The same reduction was noted in Ref. 16 for tests of A325 bolts.

After failure, the bolt was fitted together as well as possible and the final measurement of elongation was made with the C-frame extensometer. It should be noted that this practice was not started until very late in the testing program and was done for only a few of the direct and torqued tension tests, but for all of the special tests conducted. Prior to this, initial and final elongations were taken with a steel scale with .01 inch divisions. This proved to be very erratic, and therefore, although final elongations are reported for the direct and torqued tension tests, they should be considered only as rough approximations.

Additional details of this testing procedure and many of those to follow are reported in References 14 and 24.

2.5 TORQUED TENSION TESTING PROCEDURE

After measuring the initial length, the bolt was installed in the bolt calibrator with the proper thread length under the nut. This adjustment was obtained by using heavy packing washers to vary the gripped length. These washers had milled surfaces which provided a tight fit between adjacent washers and the bearing plate of the bolt calibrator.

The bolt head was held rigidly in place by a fitting in the bottom of the calibrator and the bolt was loaded by turning the nut against the resistance of the oil pressure built up in the load cell. Contrary to usual field practice, the calibrator was mounted so that the bolt would be in a vertical position to facilitate accurate elongation measurements with the C-frame extensometer.

The bolt was first tightened with a hand wrench to a "snug" load of eight kips (10 kips for the LI, AB, and JJ lots) and then by turning the nut with the impact wrench in 45° (1/8-turn) increments until failure. Tightening was stopped at each increment and load and elongation readings were taken. After failure the final elongation was measured, in most cases with a steel scale, and type of failure was recorded. This general procedure was followed for all tests in which wrench tightening was involved.

2.6 TESTING PROCEDURE FOR COMBINED TORQUED-DIRECT TENSION TESTS

The tests of bolts loaded in direct tension after being preloaded by a given nut rotation with an impact wrench, were all conducted in the small bolt calibrator since it was the only one which was adapted to the oil pump. Because of this, the tests were limited to 7/8 inch diameter bolts. The testing procedure was as follows. The test set-up is shown in Fig. 3. The bolts were first loaded exactly as described above for torqued tension tests until 5/8 turn of the nut was reached with the impact wrench. Then the oil pump was brought up to a pressure equivalent to that in the load cell for the bolt tension indicated. The valve between load cell and pump was then opened and the load was allowed to stabilize. The resulting change in load was never more than about one kip in either direction. The extensometer was then placed on the bolt and the bolt was loaded directly with the oil pump without further nut rotation. Loads and elongations were taken at small intervals until several readings had been taken beyond the ultimate load. Finally, the extensometer was removed and pumping continued until bolt failure. Final elongation was measured with the extensometer and the type of failure was recorded.

2.7 TESTING PROCEDURE FOR REPEATED WRENCH INSTALLATION OF BOLTS

The testing proceeded exactly as for the regular torqued tension tests discussed above, except that after a specified nut rotation, the nut was loosened until all load was removed. This procedure was repeated as often as required until bolt failure. Final load, elongation and number of cycles to failure were then recorded. These tests were conducted to determine the effects of reinstallation of alloy steel bolts in the field. Heavy thread lubricant was not used for these tests.

2.8 PROCEDURE FOR TESTING BOLTS INSTALLED IN STEEL PLATE

Because these bolts were installed in steel plates, bolt load was not recorded during these tests. However, load readings were not required since it was assumed that the load-elongation relationship established by regular torqued tension tests was applicable to the bolts torqued in steel plates. Measured elongations for a given nut rotation in the plate could be related directly to the torqued load curve and the magnitude of the induced preload ascertained.

The bolts were installed in the steel plate to the elongation corresponding to "snug" load of the regular torqued tension tests, then the bolt was loaded to failure in 45° increments. Elongation was measured at each increment. The LI bolts were tested using a solid block of A440 steel, measuring 4 inches on each side with a 15/16 inch diameter hole through it. The ED bolts were tested with four one inch plies of A440 steel having the same overall dimensions as above. All remaining lots were tested in the bolt calibrators with all oil removed and the cylinder bearing against the casing of the cell. Packing washers were used to provide the proper grip. The results of this latter method were found to be consistent with those using the A440 steel blocks and plates and was by far the easiest of accomplishment. Again, these tests were conducted with only shipping oil on the threads.

2.9 TEST PROCEDURE FOR CONTINUOUSLY TORQUED BOLTS

A number of bolts were continuously torqued for comparison with bolts torqued by incremental nut rotation. The bolts were installed continuously to a specified nut rotation, which is common field procedure.

They were snugged with a hand wrench then tightened with the impact wrench in the bolt calibrator and, when the specified nut rotation was reached, the load and elongation were recorded. The results were then compared to the regular torqued tension tests. The bolts were not tested to failure.

3. RESULTS AND ANALYSIS

3.1 COUPON TESTS

The results of all bolt coupon tests are listed in Table 4 and compared to minimum values specified by ASTM. All values for strength and ductility exceeded specified minimum values except the tensile strength for lot BD which was 98% of the specified value. The elongations listed are for a gage length of 1.9 inches rather than the two inches specified by ASTM. However, these values exceed the specified values by a large margin except for the BD lot, and would without doubt have been adequate with a two inch gage length.

Figure 5 shows a typical stress-strain curve for three coupons cut from lot KK, A490 bolts. The curve is somewhat similar to typical curves for high strength alloy steel, exhibiting a well defined elastic limit and a fairly high ratio of yield to ultimate stress. This figure is typical of most of the coupon tests conducted. There was very little scatter of individual test points. A photograph comparing coupons before and after testing is shown in Figure 6 to depict graphically the amount of elongation and reduction in area experienced. The broken specimens could all be fitted back together very closely which resulted in accurate measurements of final elongation.

Figure 7 is included as a point of interest. It shows typical fractures for the A354 BC bolt coupon on the left and the A354 BD (or A490) coupon on the right. The higher strength A354 BD coupons nearly always exhibit a very jagged fracture compared to the relatively uniform fracture of the A354 BC coupons. About half of the A354 BC coupons had partially developed cone and cup fractures. It was also noticed that a few of the coupons had longitudinal faults which opened during testing. This is thought to be a result of fast cooling of the bolt during heat treatment. No decrease in tensile strength or ductility was evident for these coupons. Figure 8 shows one of the A354 BC coupons with this longitudinal fault.

3.2 HARDNESS TESTS

Table 5 lists the results of the hardness tests for each bolt lot, indicating results of both Brinell and Rockwell C tests. These values all fall within the range specified in the applicable ASTM specification. This table also lists the tensile strength for each lot of bolts, tested according to ASTM designation A370. Tensile strength is discussed in more detail in the next section. It is mentioned here only to point out that no good correlation can be seen between the higher hardnesses and the higher tensile strengths reported. Neither do the hardness values compare consistently with each other. However, the results do serve their intended purpose in providing still another check that the bolts tested met ASTM specifications.

3.3 DIRECT TENSION TESTS

Figure 9 shows typical results of direct tension tests of the

A354 BD (or A490) bolt, in this case the ED lot. The bolt is still linearly elastic at proof load and the elastic limit is not very well defined. High stress concentrations in the threads cause initial yielding to take place over a large range of load. After reaching ultimate load, the bolts had less capacity for further deformation than did the coupons, due to restraint caused by the shank and nut and to the relatively short gage length of the highly stressed threaded portion.

A number of direct tension tests were conducted with approximately six threads under the nut as specified by ASTM designation A370. The ultimate tensile strength for each of these lots is reported in Table 5 along with the percent of that specified by ASTM. Bolt strength varied from 102 to 113 percent of that specified by ASTM. If these percentages are compared lot by lot with those from the coupon tests recorded in Table 4, it will be noticed that there is usually close agreement between the two. Further inspection will indicate that the largest discrepancies occur for the one inch diameter bolts (lots BC, DC, BD, and FD) and that the coupon strengths are always the lower of the two values. For example, the BD lot coupon tests indicated that the mean tensile strength was 98% of the required tensile strength, while the mean ultimate load of the bolts tested was 110% of that specified. If the increase of bolt strength over coupon strength were a constant ratio, it could be ascribed to differences in test methods or to small inaccuracies in the concept of stress area. However, since the effect becomes much more pronounced with the larger diameter bolt, it is reasonable to believe that this is the result of a decreasing effect of heat treatment near the center of the larger bolt. The longitudinal cracks noticed in some of the coupons testify to the presence of a large temperature gradient at some time during bolt manufacture. It should be noted that ASTM specification A370 requires that coupons be cut at mid radius for bolt diameters of $1\frac{1}{2}$ inches and more to counter this reduction in effect of heat treatment.

A complete tabulation of test results for all bolts tested in direct tension is given in Table 6, showing the tensile strength and its standard deviation, the load at rupture, and the elongations at proof load, ultimate load and rupture load.

Standard deviations were computed in the following way, as suggested for samples of less than 30 specimens.

$$\sigma = \pm \sqrt{\frac{\sum (x-\bar{x})^2}{n-1}}$$

where

σ = standard deviation

x = individual test value of the variable in question

$\bar{x}$ = mean value of the variable from all tests

n = number of tests conducted

This formula was also used for the calculations of standard deviations listed in Tables 8 and 9.

A study of Table 6 indicates that bolts with short lengths of thread under the nut have significantly higher tensile strengths and lower failure elongations than bolts from the same lot tested with more thread under the nut. Figure 10 graphically depicts the effect of thread length under the nut on the direct tensile strength of one lot of A490 bolts. It will be seen later that this is true also for the torqued tension tests. This higher strength is partially the result of a small decrease in thread depth near the thread runout which results in a somewhat larger cross sectional area. This increase in strength may also be due to the fact that failure is forced to occur over a relatively short length of thread. Tests of bolts having a larger thread length under the nut normally failed on a diagonal plane for both the direct and torqued tension tests as indicated in part (a) of Fig. 11, while for the shorter length of thread under the nut, the failure planes were not nearly as inclined, as shown in part (b) of Fig. 11. This change in the plane of failure, together with the larger restraint to lateral contraction caused by the proximity of nut and bolt shank to the zone of maximum stress, resulted in increased tensile strength. Because of the short length of the highly stressed threaded portion, elongation capacity is reduced for short thread lengths under the nut (see Fig. 10).

For the alloy steel bolts tested with little thread in grip, the mode of failure was a combined tensile and shearing fracture, usually similar to a cone and cup fracture (although far from perfect). Two bolts with short threads failed by thread stripping but only after an ultimate load well above the specified minimum tensile strength had been reached. As previously stated, with more thread length under the nut, the fracture became a diagonal one extending over several threads, with shear predominating as the mode of failure. A comparison for typical fractures with short and long thread length under the nut is made for the direct tension tests on the left side of Fig. 11.

A comparison of the behavior in direct tension of the A325, A354BC and A490 (or A354BD) bolts is made in Fig. 12. The curves shown are for bolts having nearly equal grip lengths and thread lengths under the nut. It is readily apparent that as the bolt strength increases it is accompanied by a corresponding decrease in deformation capacity.

Although a threaded fastener is not a simple tension bar, its elastic behavior may be computed by using a few simplifying assumptions. First the threaded portion is considered as a uniform shaft having a cross sectional area equal to the stress area listed in the ASTM specification for the bolt in question. Secondly it is assumed that the full tensile load in the bolt is carried between the inner face of the bolt head and a point centered between the two faces of the nut. It is further assumed that no stress causing axial deformation exists beyond these limits. The total elongation of the bolt, as measured by the C-frame extensometer, at any given elastic load can then be computed from the formula:

$$\delta = \frac{P}{E} \sum \frac{L}{A}$$

where δ = total axial deformation inches

P = axial load, kips

E = modulus of elasticity, kips per square inch

L = length, inches

A = cross sectional area, square inches

For example, for lot AC-9-2S, Table 1 lists the values of g and t as 3-5/8 inches and 1/8 inch respectively. From ASA B18.2, the mean thickness of a 7/8 inch heavy semifinished hexagon nut is 0.859 inches. These values result in a shank length of 3½ inches and a stressed thread length of 0.554 inches. The cross sectional area of the 7/8 inch shank is 0.601 sq. inches. and the stress area of the threaded portion, taken from the A354 specification is 0.462 sq. inches. Substituting these values into the above equation, the elongation of the bolt at its proof load of 48.5 kips is found to be:

$$\delta = \frac{48.5}{29{,}500}\left[\frac{3.5}{0.601} + \frac{0.554}{0.462}\right] = 0.0115 \text{ inches,}$$

which is extremely close to the experimentally determined value of 0.0114 inches listed in Table 7. This table lists the computed elongations at proof load for each of the lots tested and the experimentally determined values for the direct and torqued tension tests. All computed values compared extremely well to the direct tension results, with a maximum error of about eight percent. The comparison with the torqued tension results will be discussed later.

3.4 TORQUED TENSION TESTS

As previously stated two series of torqued tension tests were conducted, one with a heavy commercial lubricant applied to the threads of bolt and nut, the other with only a light shipping oil, or simulated shipping oil in the case of the four lots of A354 BC bolts. In all other respects the procedures of the two series were identical. Figure 13 shows the load-elongation relationship in torqued tension with threads as received for the ED lot A354 BD bolt. This curve indicates a scatter of individual results somewhat greater than noted in Fig. 9 for the direct tension tests. The load at 1/2 turn is seen to be just above proof load, which is the preload specified[13] for installation of A325 and A490 bolts, and only slightly into the inelastic range. In Fig. 14 is shown the same torqued tension relationship with the threads heavily lubricated. No major changes in behavior are apparent except that the scatter of individual results has been reduced.

Table 8 shows the results of torqued tension tests of bolts coated with shipping oil, while Table 9 lists the results of tests of bolts coated with the heavy lubricant. These tables show the mean values of load at 1/2 turn of nut from snug; torqued tensile strength; rupture load, and the elongations at proof load, at 1/2 turn of nut; at ultimate load, and after rupture. The nut rotation from snug to failure is also listed as is the standard deviation of the mean values of tensile strength and the percent of the torqued ultimate load to that in direct tension for the same lot. In addition to these values, Table 8 reports values of load and elongation at 5/8 turn of nut from snug. These values are reported since they are the closest available to the 2/3 turn specified in the 1964 specification of the Research Council for A490 bolts having lengths under head greater than eight inches or eight diameters whichever is the smaller. Both of these tables list only the results of tests conducted in the bolt calibrators.

The tests of bolts gripping steel plate are discussed later.

The mean curves of Figs. 9, 13, and 14 are reproduced in Fig. 15 for comparison of the results of the different types of tests. The ultimate strength in direct tension is seen to be substantially greater than that in torqued tension. This increase has been noted by many investigators[16, 18, 19, 20, 25] for the A325, A354, and A490 bolts. Thread lubrication provides a slight increase in torqued tensile strength, but in no other way can it be seen to affect the torqued tension behavior. In this figure the elongations at failure for the torqued tension tests are seen to be nearly equal to that in direct tension. For most lots the elongation in direct tension was greater than in torqued tension. However, because of the early inaccuracies in measurement of final elongation, no further discussion is warranted.

The reduction in tensile strength for torqued tension tests of bolts has been explained theoretically using both the principal stress theory[25, 26] and the principal strain theory[25]. Lubrication could allow a higher ultimate tensile strength because the shear stress component induced by torque is reduced. Lubrication is thought to have such a small effect because the high bearing stresses encountered cause the structure of the lubricant to break down[26].

This reduction in tensile strength is seen to be present for all of the torqued tension tests listed in Tables 8 and 9. The percentage of torqued tension ultimate strength to direct tensile strength is recorded in both tables and averages about 85% for threads coated with shipping oil and about 88% for heavily lubricated threads. For the A354 BC bolt, proof load is 84% of specified tensile strength and for the A354 BD and A490 bolts, proof load is 80% of specified tensile strength. Had the bolts tested in this program been minimum strength bolts, some of the lots may have had ultimate strengths in torqued tension below proof load. Regardless of the nut rotation specified, proof load could not be induced in such bolts. The A325 bolt with a ratio of proof load to specified tensile strength of 0.70 has been found to be practically immune to this phenomenon.

Figure 16 allows comparison of the typical behavior of A325, A354 BC and A354 BD (or A490) bolts in torqued tension. Each lot shown was tested with 3/4 inch thread under the nut and a grip length of either $4\frac{1}{4}$ or $4\frac{1}{2}$ inches. As with the comparison of direct tension tests, the higher strength bolts show smaller elongations to failure. The higher strength bolt also reaches ultimate load at a smaller elongation and the load then drops off more quickly than the A325 bolt. This was also true for the direct tension relationships shown in Fig. 12.

Another interesting point is that the mean elongation at $\frac{1}{2}$ turn is nearly identical for each of these curves. Results given in Tables 8 and 9 indicate that the elongation at $\frac{1}{2}$ turn remains fairly constant for most of the bolts tested. For the higher strength, long grip bolt this elongation may be entirely due to elastic deformations, whereas for the lower strength bolt both elastic and inelastic deformations may be included. For example, Fig. 17 compares the torqued tension behavior of A325 bolts with a grip length of $8\frac{1}{4}$ inches to that of A490 bolts with a grip length of 8-11/16 inches. The elongation and load at ½ turn of nut are nearly identical for the two bolt lots. The half turn is well into the inelastic range and above proof load for the A325 bolt, however, it is in the elastic range and well below proof load for the A490 bolt. In general, as bolt strength and grip length increase so does the elongation to the elastic limit or proof load. The compressive deformation of the material being gripped also increases with higher bolt tension. These effects combine to require larger nut rotations to induce proof load in the high strength bolts, especially those with long grip lengths.

A study of Fig. 18 yields further interesting results. This figure is a bar graph of the loads at ½ and 5/8 turn and the ultimate load for the A354 BD and A490 bolts taken from Table 8 for torqued tension tests with threads as received. The load scale is non-dimensionalized by dividing all loads by the proof load so that both 7/8 and 1 inch bolts may be compared. The ultimate load is shown to indicate the remaining load available at ½ and 5/8 turn of nut. The load at 1/2 turn of nut is consistently below proof load for the bolts with longer grip lengths for reasons just presented. Even at 5/8 turn of nut, two of the lots with longer grips had mean loads below proof load. Thread length under the nut showed no consistent effects on the loads at ½ and 5/8 turn. Thread lubrication did nothing to improve this behavior as can be seen in Table 9. Although the load at ½ turn of nut was above proof load for most of the bolts with short grip lengths, it usually remained within the elastic range and was therefore very sensitive to minor changes in elongation.

The effects of grip length on the load-elongation relationship of the alloy steel bolt are illustrated in Fig. 19 for two lots of 7/8 inch A490 bolts. Both lots had the same thread length under nut. The relationship for the shorter bolt, shown by the solid line has a steeper elastic slope than that for the longer bolt and, although the elongations at $\frac{1}{2}$ turn of nut are approximately equal for the two lots, the resulting load is above proof load for the shorter grip bolt and below proof load for the longer.

The elastic behavior of bolts in torqued tension is nearly the same as in direct tension and can be computed in the same way. Table 7 shows the comparison between the computed values of elongation at proof load and the measured values in torqued tension taken from Tables 8 and 9. The correlation, while not as close as for the direct tests, is still reasonably good. Where major discrepancies occur, they are due to inelastic behavior below proof load. In general, the elastic limit is decreased from its direct tension value in about the same ratio as the torqued tension ultimate strength is decreased below that in direct tension. Hence, for these bolts, where inelastic deformations are not present, the induced preload due to a specified elongation can be predicted. Noting that the elongation at a given nut rotation seems to remain approximately constant, it may even be possible that, with further study, the preload at a specified nut rotation can be predicted. This has possible significance in the development of future installation and inspection methods.

Figure 20 emphasizes the differences resulting from tests of the same lot of bolts with different lengths of thread under the nut. As with the direct tension tests, a shorter length of thread under the nut results in a higher ultimate load. The reasons for this are the same as for the direct tension tests. This behavior was not appreciably affected by thread lubrication. It was true for A354 BC, A354 BD and A490 bolts and has also been reported for A325 bolts[16]. Although not evident for this lot of bolts, the elongation at failure was nearly always less for the short length of thread under the nut, due to the relatively short highly stressed threaded area. The figure also indicates a decrease in the elastic slope for the longer thread length under the nut, as would be expected.

The nut rotation to failure ranged from 1 to 1-7/8 revolutions for torqued tension tests with threads as received and from 1-1/8 to 1-7/8 revolutions with lubricated threads. Lubrication had no significant effect on the rotation to failure. The nut rotation to failure is plotted versus the thread length under nut for the 7/8 inch bolts in Fig. 21. Mean curves are shown in the figure, one for A354 BC bolts, one for A354 BD and A490 bolts, and one taken from Ref. 16 for A325 bolts. In all three cases there is an increase in the nut rotation to failure with an increase in the thread length under the nut. While this is very pronounced for A325 bolts, the increase for alloy steel bolts is less. The one inch diameter alloy steel bolts show trends much like the 7/8 inch bolts. Increased nut rotation to failure depends directly on the increased elongation capacity of bolts with greater thread length under nut. The more the bolt stretches, the greater is the nut rotation that must be applied to cause bolt failure.

For the torqued tension tests, fractures are caused by a combination of tensile and torsional shear stresses. Figure 11 shows comparisons between bolt failures caused by direct tension on the left and torqued tension on the right for both short and long thread lengths under nut. A definite twisting pattern is visible on the fractured surface of the bolts tested in torqued tension.

3.5 COMBINED TORQUED-DIRECT TENSION TESTS

Figure 22 graphically depicts the results of this study. The bolts were first tightened to 5/8 turn from snug and then loaded in direct tension with the pump shown in Fig. 3. The transfer from torqued to direct tension is indicated by the sharp turn upward of the load-elongation relationship. The curve then quickly approaches the direct tension curve for the same lot of bolts, shown as a dashed line. The curve showing the load-elongation relationship in torqued tension with threads as received is also included as a frame of reference. Bolt fractures were all similar to those in direct tension with no visible influence of torsional shearing stresses.

A summary of the results of bolts tested in direct tension after first being wrench tightened to 5/8 turn from snug is given in Table 10. One lot of A354 BC bolts and three lots of A490 bolts were tested in this manner. The nut rotation of 5/8 turn was purposely specified for these tests to study the possibly severe effects of loads in the inelastic range and near the ultimate strength in torqued tension. The mean ultimate load for each lot of bolts is given and compared to the ultimate load of the same lot in direct tension. The mean ultimate loads reached during these tests ranged from 97 to 103 percent of the corresponding value in direct tension, not a significant variation.

3.6 REPEATED WRENCH INSTALLATION

The results of repeated installation tests of alloy steel bolts are shown in Table 11. This table shows the nut rotation to which each bolt was installed, the load at the completion of each cycle and the mean number of cycles to failure. Twelve A354 BC bolts and six A490 bolts were tested, each with cycles of 3/4 turn of nut except one lot of A354 BC bolts which was tightened to ½ turn. It should be noted that these bolts were tested without heavy thread lubrication. This table indicates the deleterious reaction of these bolts to repetitive torquing. In all cases, the load at the end of each successive cycle was lower than for the previous cycle. No more than three cycles of installation were completed before failure for the bolts tightened to 3/4 turn of nut, while the lot tightened to ½ turn withstood an average of four cycles before failure. What is not shown in this table is the rapid increase in required installation time after the first installation. For every bolt tested the installation time for the second cycle was nearly triple that of the first. Because of the incremental nature of testing, this increase in time was not measures precisely or recorded.

The behavior of these bolts was much more severe than that reported for tests of A325 bolts[16]. This severity is the result of greater cumulative thread damage caused by high loads and high stress concentrations acting on threads of the same geometry as the threads on the A325 bolts. The behavior of the A490 bolts seemed to be no more critical than that of the A354 BC bolts. However, a direct comparison is difficult for the limited number of tests conducted.

Figure 23 illustrates the relationship between load and elongation for repetitive torquing to 3/4 turn of nut of one of the A354 BC bolts with a thread length under the nut of 11/16 inch. The solid test points indicate 3/4 turn of nut. The dashed curve shows the corresponding torqued tension calibration. As shown in the figure, the ultimate strength of the bolt was exceeded before completion of the first cycle. Because the ultimate strength was exceeded at 3/4 turn of nut, three more bolts from the same lot were tested in cycles of ½ turn of nut. A representative plot of their behavior is shown in Fig. 24. This time the ultimate strength of the bolt was not reached until the second loading cycle and failure occurred after an average of three full cycles had been completed.

The BC lot bolts tested in this series all exhibited load-elongation characteristics on the first cycle of installation which were slightly weaker than the mean torqued tension curve established by the tests reported in Section 3.4. In general they were within the lower limit of the scatter band of the regular torqued tension curve.

3.7 BOLTS INSTALLED IN STEEL PLATE

Table 12 summarizes the results obtained from tests of bolts installed in steel plates rather than in the hydraulic bolt calibrator. Three A354 BC bolts, nine A354 BD bolts and twenty-one A490 bolts were tested. The table lists mean experimental values of elongation at ½ turn of nut, elongation after rupture, and nut rotation to failure. Also listed is the computed load at ½ turn, determined from the measured bolt elongation as applied to the mean torqued tension load-elongation curve for tests of the same lot of bolts in the bolt calibrator. This load is then tabulated as a percent of the load at ½ turn for torqued tension tests of the bolts tested in the bolt calibrator.

The computation of load at ½ turn of nut from the load-elongation relationship found in the bolt calibrator is made possible by the assumption that the mean load-elongation relationship for a given lot of bolts is a property of the bolts themselves and is independent of the testing conditions and bearing material used to resist the applied load.

The most striking result indicated in the table is that the elongation at ½ turn of nut for bolts turned in solid plate averages about 0.03 inches while in the bolt calibrator the average elongation was closer to 0.02 inches for the same lots (see Table 8). For the bolts with short grip lengths this caused an increase of from 2 to 14 percent in the load at ½ turn above that found in the bolt calibrator. For the one lot of bolts tested with a long grip length (lot GD) the load at ½ turn showed a 92 percent increase from 32.7 to 63 kips. Apparently the elongation and corresponding tension of a bolt tightened to a given nut rotation in a well compacted joint may be substantially above the values obtained using a hydraulic bolt calibrator. In the last two columns of this table are shown the nut rotations to failure for these tests and those listed in Table 8 for the regular torqued tension tests. It will be seen that, in the steel plate, rotation to failure averages about 1/8 turn less than for the tests conducted in the bolt calibrator. It is apparent that the increased deformation of the bolt calibrator results in an increase in the nut rotation required to cause failure.

The results of this type of test are shown in Figs. 25 and 26 for the ED lot of A354 BD bolts torqued gripping 4 one inch plies of A440 steel, 4 inches square in lieu of the bolt calibrator. At the top of Fig. 25 are plotted the relationships for nut rotation versus elongation. The solid test points are for the bolts tested in the bolt calibrator and the open points are for those tested in the steel plate. Bolts torqued in steel plate to a given nut rotation resulted in a greater bolt elongation than in the bolt calibrator. This is because the stiffer plate deforms less than the bolt calibrator thus causing more elongation in the bolt for a given nut rotation.

As shown in Fig. 27 the change in length, Δa , of an assembly between the free face of the nut and the threaded end of the bolt must be equal to the distance the nut is rotated down the thread and is composed of four parts: the compressive deformations of the nut, the gripped material, and the bolt head, and the elongation of the shank and threaded portion of the bolt. Ideally, if the bolt head, the nut and the gripped material were completely rigid the entire deformation would be in the form of elongation of the bolt shank and threads. For one revolution of the nut, this deformation must be equal to the distance between threads. This ideal behavior is shown as a dashed curve in Fig. 25. The three curves shown at the top of the figure all originate at the mean snug elongation of 0.0025 inches as measured during the torqued tension calibration. Bolts in the steel plate were purposely snugged to this elongation.

The bottom half of Fig. 25 is the mean relationship between bolt tension and elongation for this lot of bolts in torqued tension (see Fig. 13). If the elongations at ½ turn are projected down from the curves above, the difference in loads at ½ turn of nut is readily seen.

By projecting the elongations from the elongation-rotation curves onto the mean load-elongation curve in this manner, load versus nut rotation relationships can be plotted for the solid plate tests and for the ideal case of completely rigid bolt head, nut, and gripped material. These relationships are plotted in Fig. 26. The shape of the curve for the ideal case is the same as the load-elongation curve since there is a direct relationship in this case between nut rotation and bolt elongation. The computed curve for the solid plates deviates from this curve at a constant rate, indicating the flexibility of the system. Proof load was reached in this case at just over ¼ turn of nut. The load-rotation curve obtained in the bolt calibrator is also compared with the ideal and solid plate curves in Fig. 26. This curve indicates the greatest flexibility with large deformation at small rotations indicating a slight amount of play in the hydraulic system itself, probably due to entrapped air. Proof load was not reached in this case until just under ½ turn of nut. These three curves also indicate smaller nut rotations to failure for the stiffer assemblies.

3.8 CONTINUOUSLY TORQUED BOLTS

Two lots of A354 BC and three lots of A490 bolts were torqued continuously to either ½ or 3/4 turn of nut for the purpose of determining whether the bolts were affected by incremental tightening. The resulting variation was no more than ten percent in either direction for load or elongation at the specified number of turns. Figure 28 shows the correlation between the two methods for the AD lot 7/8 inch A490 bolts. The continuously torqued bolts are indicated by the solid test points which are superimposed on the load deformation relationship for the same bolts incrementally torqued. Neither the load nor elongation at 3/4 turn of nut is perceptibly affected.

3.9 RECOMMENDATIONS

The reduced ultimate load for these bolts in torqued tension together with the high ratio of proof load to specified ultimate load (0.80) for the A354 BD and A490 bolts make it advisable to specify a minimum preload for installation, somewhat less than proof load. For bolts used in the field it is highly possible that the ultimate load in torqued tension could be less than 80 percent of that in direct tension. For minimum strength bolts this would be less than proof load. It is suggested that alloy steel bolts be installed to 70 percent of minimum tensile strength, in the range of proof load to ultimate that has long been satisfactorily used with A325 bolts.

Because of the differences in the load versus nut rotation behavior between tests conducted in steel plate and in the bolt calibrator, it is proposed that this relationship be studied further. Measurements on actual joints would be very helpful.

From all presently available information, it is believed that the hydraulic bolt calibrator can be used for torqued tension tests as a conservative estimate of the lower bound of the stiffness of well compacted prototype joints.

4. SUMMARY

As a result of study of the tests conducted under this program, the following conclusions and recommendations have been made. They apply directly to the tests reported herein and care must be used in generalizing some of them. The recommendations are based on the results of these tests and experience gained from the work of others.

1. Coupon tests do not accurately reflect the true strength of a bolt when cut concentrically with the bolt axis, primarily because of the reduced effect of heat treatment near the center of the bolt. The variation was more pronounced for the one inch bolts than for the 7/8 inch bolts as is evident in Table 4.

2. The elastic behavior of high strength bolts in direct and torqued tension can be predicted using the simple theory for deformation of axially loaded members. Correlation with test results is excellent (Table 7).

3. All bolts had lower ultimate loads when tested in torqued tension than in direct tension. Ultimate loads of bolts torqued with only shipping oil as a lubricant varied from 78 to 92 percent of those in direct tension with an average value of about 85 percent. Heavy lubrication resulted in slightly increased torqued ultimate loads for the A354 BD and A490 bolts with short lengths of thread under the nut (Fig. 15).

4. A decrease in the length of thread under the nut resulted

in increased ultimate strength and reduced elongation capacity for both direct and torqued tension tests of alloy steel bolts (Fig. 10, 20). These effects have also been noted by other investigators for A325 bolts[16].

5. When bolts were tested in the hydraulic bolt calibrator, the preload induced by one half turn of nut exceeded proof load for all lots of A354 BC bolts and for most of the A354 BD and A490 bolts with short grip lengths. However, these loads usually remained in the elastic range and were therefore subject to large variations for relatively small variations in elongation. For the A354 BD and A490 bolts with grip lengths above seven inches, proof load could not be induced by ½ turn of nut. Even at 5/8 turn of nut, the preload induced in the bolt calibrator was often less than proof load. At 3/4 turn of nut, the induced preload finally moved above proof load and partially into the inelastic range for these long grip lengths (Fig. 19).

6. Tests of A354 and A490 bolts tightened in steel plate indicate that fewer turns of nut are required to induce a given preload than in the bolt calibrator (Fig. 26). Less nut rotation to failure was also observed in steel plate. These effects are due to the inherent flexibility of the bolt calibrator under load.

7. The one inch diameter A354 BC bolts behaved in a somewhat more brittle manner than 7/8 inch bolts of the same specification. This is most noticeable for the torqued tension tests where both elongation after fracture and turns to failure are consistently lower for the one inch bolts regardless of thread lubrication. The nut rotation to failure averages about ¼ turn less for the one inch bolts than

for the 7/8 inch bolts. No similar results can be seen for the A354 BD or A490 bolts.

8. Except for providing a higher ultimate strength in torqued tension for the A354 BD and A490 bolts with short thread lengths under nut, heavy thread lubrication had little apparent effect. For the A354 BC bolts, the freshly applied shipping oil seemed to be slightly more beneficial in producing high ultimate loads and large nut rotations to failure than the heavy lubricant (Tables 8, 9).

9. Nut rotations from snug were found to vary from 1 to nearly 2 full revolutions before bolt failure, increasing with increased thread length under the nut. In general, the A354 BC bolt withstood more turns to failure than the A354 BD or A490 bolt. The increase in nut rotation to failure with increased thread under nut is also noted for A325[16] bolts although to a much greater degree as shown in Fig. 21.

10. Tests of bolts in direct tension after having been preloaded with a wrench indicate that no reduction in direct tensile ultimate strength exists (Fig. 22).

11. Repeated tightening of alloy steel bolts into the inelastic range resulted in a marked reduction in induced tension with each installation and a marked increase in installation time. Very few cycles of load could be applied before bolt failure (Fig. 23, 24).

12. The behavior of alloy steel bolts torqued continuously to a given nut rotation is no different than that of incrementally tightened bolts, as shown in Fig. 28.

13. It is recommended that consideration be given to specifying an installed preload less than the proof load for alloy steel bolts.

14. The hydraulic bolt calibrator yields a conservative estimate of the load versus nut rotation relationship to be expected for bolts tightened in a well compacted joint.

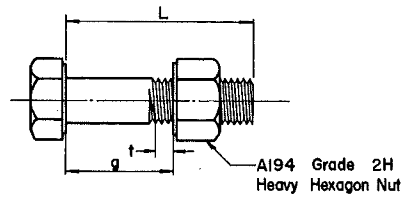
5. GLOSSARY

AISI	American Iron and Steel Institute
ASA	American Standards Association
ASTM	American Society for Testing and Materials
direct tension	tension produced in a bolt with no accompanying torsion or shear
grip	the distance between bearing faces of bolt head and nut
kip	one thousand pounds
proof load	a minimum elastic limit specified for high strength bolts by ASTM
psig	pressure above atmospheric, pounds per square inch
Research Council	The Research Council on Riveted and Bolted Structural Joints of the Engineering Foundation
snug, snugged	an arbitrarily defined load said to be that which a man can reach using a spud wrench, or at which an impact wrench will start to impact solidly
stress area	the effective stress resisting area of the threaded portion of a bolt; defined in ASTM specifications
thread under nut, thread in grip	the distance from the bearing face of the nut to the last thread of full depth
threads as received	threads with only a light shipping oil present, no heavy lubrication
torqued tension	tension induced in a bolt by rotating the nut with a wrench

6. TABLES AND FIGURES

TABLE 1

DESCRIPTION OF SPECIMENS



Bolt Lot	ASTM Designation	Head* Type	Nominal Diameter, inches	Type of Thread	L inches	g inches	t inches
AC-7-2S	A354BC	H	7/8	Cut	5.25	3.62	0.125
AC-7-9S	"	H	7/8	"	"	4.06	0.562
BC-8-2S	"	H	1	"	"	3.37	0.125
BC-8-11S	"	H	1	"	"	3.94	0.688
CC-7-12S	"	R	7/8	Rolled	5.50	4.25	0.75
DC-8-16S	"	R	1	"	"	"	1.00
AD-7-2S	A490	H	7/8	Cut	5.25	3.62	0.125
AD-7-9S	"	H	7/8	"	"	4.06	0.562
BD-8-2S	"	H	1	"	"	3.37	0.125
BD-8-11S	"	H	1	"	"	3.94	0.688
CD-7-2L	"	H	7/8	"	9.25	7.62	0.125
CD-7-9L	"	H	7/8	"	"	8.06	0.562
DD-8-2L	"	H	1	"	"	7.37	0.125
DD-8-11L	"	H	1	"	"	7.94	0.688
ED-7-12S	A354BD	R	7/8	Rolled	5.50	4.25	0.75
FD-8-16S	"	R	1	"	"	"	1.00
GD-7-12L	"	R	7/8	Cut	9.50	8.00	0.75
HD-8-16L	"	R	1	"	"	7.75	1.00
LI-7-2S	A490	H	7/8	Rolled	5.50	4.12	0.125
LI-7-9S	"	H	7/8	"	"	4.56	0.562
AB-7-2L	"	H	7/8	Cut	9.50	8.25	0.125
AB-7-9L	"	H	7/8	"	"	8.69	0.562
KK-7-3S	"	H	7/8	Rolled	5.50	4.19	0.188
JJ-8-6S	"	H	1	"	"	4.12	0.375

*From American Standards Assoc. B18.2: H identifies Heavy Semi-finished Hexagon Head
R identifies Regular Semi-finished Hexagon Head

TABLE 2

SPECIFIED PHYSICAL PROPERTIES

Bolt Diameter, inches	Stress Area, sq. in.	ASTM Designation	Coupon Properties			Bolt Properties			
			Tensile Strength, min, ksi	% Elong. in 2 inches min.	% Red. of area min.	Proof Load, min, kips	Tensile* Strength min, kips	Hardness, Rockwell C	Hardness, Brinell
7/8	0.462	A325	-	-	-	36.05	53.15	22-34	235-321
"	"	A354BC	125	16	50	48.50	57.75	25-34	255-321
"	"	A354BD	150	14	35	55.45	69.30	32-38	302-352
"	"	A490	150	14	35	55.45	69.30	32-38	302-352
1	0.606	A325	-	-	-	47.25	69.70	22-34	235-321
"	"	A354BC	125	16	50	63.65	75.75	25-34	255-321
"	"	A354BD	150	14	35	72.70	90.90	32-38	302-352
"	"	A490	150	14	35	72.70	90.90	32-38	302-352

*Specified for bolts tested with 6 full threads under the nut, according to ASTM Designation A370, Supplement III

TABLE 3

TEST PROGRAM

Bolt Lot	ASTM Designation	Number of Specimens Tested						
		Direct Tension	Torqued Tension, threads as received	Torqued Tension, threads lubricated	Combined Torqued-Direct Tension	Repeated Wrench Installation	Bolts Installed in Steel Plate	Continuously Torqued Bolts
AC-7-2S	A354BC	3	3	3				
AC-7-9S	"	3	3	3	3	3		
BC-8-2S	"	3	3	3		3		3
BC-8-11S	"	3	3	3		6	3	4
CC-7-12S	"	3	3	3				
DC-8-16S	"	3	3	3				
AD-7-2S	A490	3	3	3	2			
AD-7-9S	"	3	3	3	3	3		3
BD-8-2S	"	3	3	3			3	
BD-8-11S	"	3	3	3			3	4
CD-7-2L	"	3	3	3				
CD-7-9L	"	3	4	3	3	3		
DD-8-2L	"	3	3	3				
DD-8-11L	"	3	3	3				2
ED-7-12S	A354BD	3	4	3			3	
FD-8-16S	"	3	3	3			3	
GD-7-12L	"	3	3	3			3	
HD-8-16L	"	3	3	3				
LI-7-2S	A490	5	5				5	
LI-7-9S	"	5	5				5	
AB-7-2L	"	5	6					
AB-7-9L	"	5	5					
KK-7-3S	"	5	10				5	
JJ-8-6S	"	5	5					

TABLE 4

COUPON TEST RESULTS

Bolt Lot	ASTM Designation	Number Tested	Tensile Strength ksi	% ASTM Minimum	Elong. in 1.9"%	% ASTM Minimum	Red. of Area, %	% ASTM Minimum
AC	A354BC	3	140.3	112	21.2	132	57.2	114
BC	"	3	126.2	101	22.1	138	-	-
CC	"	3	133.0	106	21.6	135	62.2	124
DC	"	3	131.6	105	22.6	141	63.1	126
AD	A490	3	162.5	108	18.0	128	-	-
BD	"	3	147.7	98	14.6	104	59.1	169
CD	"	3	156.1	104	18.8	134	59.8	171
DD	"	3	156.6	104	19.8	142	59.8	171
ED	A354BD	3	164.9	110	16.6	118	59.1	169
FD	"	3	149.8	100	16.7	119	58.1	166
GD	"	3	160.9	107	18.8	134	58.1	166
HD	"	3	165.1	110	16.3	116	55.5	159
LI	A490	-	-	-	-	-	-	-
AB	"	3	151.6	101	21.4	153	52.9	151
KK	"	3	153.4	102	20.0	143	55.5	159
JJ	"	-	-	-	-	-	-	-

TABLE 5

COMPARISON OF BOLTS TO ASTM SPECIFICATIONS

Bolt Lot	ASTM Designation	Hardness, Rockwell C	Hardness, Brinell	Tensile Strength*		
				Number Tested	Mean, kips	% ASTM Minimum
AC-7-9S	A354BC	30	269	3	65.0	113
BC-8-11S	"	30	281	3	82.9	109
CC-7-12S	"	31	277	3	62.3	108
DC-8-16S	"	32	288	3	83.1	110
AD-7-9S	A490	34	329	3	76.5	110
BD-8-11S	"	35	328	3	100.0	110
CD-7-9L	"	35	328	3	74.5	108
DD-8-11L	"	34	304	3	96.7	106
ED-7-12S	A354BD	38	338	3	77.8	112
FD-8-16S	"	37	331	3	99.3	109
GD-7-12L	"	32	331	3	75.5	109
HD-8-16L	"	36	332	3	100.5	110
LI-7-9S	A490	34	318	5	72.1	104
AB-7-9L	"	34	307	5	70.8	102
KK	"	35	323	-	72.3+	104
JJ	"	35	323	-	-	-

*All results shown here are for approximately six threads under the nut as specified in ASTM A370

+From mill report

TABLE 6

DIRECT TENSION TEST RESULTS

Bolt Lot	ASTM Designation	Number of Specimens Tested	Ultimate Load			Rupture Load kips	Elongation, inches		
			Mean kips	Std. Dev. kips	% ASTM Minimum		At Proof Load	At Ult. Load	After Rupture
AC-7-2S	A354BC	3	72.6	1.88	126	64.3	.0114	.0854	0.173
AC-7-9S	"	3	65.0	1.57	113	52.0	.0136	.0758	0.190
BC-8-2S	"	3	91.0	2.26	120	76.3	.0115	.0783	0.140
BC-8-11S	"	3	82.9	1.60	109	61.7	.0139	.0919	0.263
CC-7-12S	"	3	62.3	0.20	108	48.7	.0139	.0900	0.300
DC-8-16S	"	3	83.1	1.22	110	64.0	.0141	.1079	0.293
AD-7-2S	A490	3	83.1	2.63	120	78.3	.0134	.0459	0.083
AD-7-9S	"	3	76.5	1.51	110	68.7	.0156	.0605	0.113
BD-8-2S	"	3	102.1	1.83	112	92.0	.0138	.0611	0.127
BD-8-11S	"	3	100.0	0.20	110	92.3	.0161	.0747	0.143
CD-7-2L	"	3	82.6	1.25	119	79.2	.0256	.0702	0.120
CD-7-9L	"	3	74.5	0.44	108	69.8	.0281	.0807	0.120
DD-8-2L	"	3	105.4	0.71	116	93.3	.0258	.0841	0.147
DD-8-11L	"	3	96.7	0.53	106	85.3	.0277	.0909	0.173
ED-7-12S	A354BD	3	77.8	0.67	112	71.7	.0159	.0619	0.120
FD-8-16S	"	3	99.3	2.18	109	81.3	.0169	.0899	0.207
GD-7-12L	"	3	75.5	0.82	109	71.0	.0275	.0839	0.137
HD-8-16L	"	3	100.5	1.25	110	91.7	.0280	.0938	0.137
LI-7-2S	A490	5	76.0	0.54	110	67.0	.0150	.0510	0.137
LI-7-9S	"	5	72.1	0.17	104	59.0	.0170	.0650	0.245
AB-7-2L	"	5	73.2	1.59	106	65.0	.0280	.0779	0.120
AB-7-9L	"	5	70.8	1.69	102	61.0	.0290	.0846	0.180
KK-7-3S	"	5	77.9	0.44	112	69.3	.0156	.0607	0.115
JJ-8-6S	"	5	99.2	1.57	109	85.0	.0160	.0625	0.189

TABLE 7

THEORETICAL ELASTIC BEHAVIOR

Bolt Lot	Proof Load kips	Calc. Elong. at Proof Load inches	Experimental Elong. at Proof Load, inches		
			Direct Tension	Torqued Tension threads as received	Torqued Tension threads lubricated
AC-7-2S	48.5	.0115	.0114	.0122	.0121
AC-7-9S	"	.0130	.0136	.0165	.0170
BC-8-2S	63.65	.0112	.0115	.0110	.0125
BC-8-11S	"	.0131	.0139	.0150	.0160
CC-7-12S	48.5	.0138	.0139	.0170	.0180
DC-8-16S	63.65	.0142	.0141	.0150	.0155
AD-7-2S	55.45	.0132	.0134	.0147	.0135
AD-7-9S	"	.0150	.0156	.0165	.0195
BD-8-2S	72.70	.0127	.0138	.0140	.0140
BD-8-11S	"	.0150	.0161	.0165	.0180
CD-7-2L	55.45	.0257	.0256	.0270	.0270
CD-7-9L	"	.0275	.0281	.0285	.0290
DD-8-2L	72.70	.0252	.0258	.0260	.0255
DD-8-11L	"	.0275	.0277	.0280	.0280
ED-7-12S	55.45	.0157	.0159	.0168	.0155
FD-8-16S	72.70	.0162	.0169	.0175	.0220
GD-7-12L	55.45	.0275	.0275	.0265	.0270
HD-8-16L	72.70	.0273	.0280	.0270	.0280
LI-7-2S	55.45	.0148	.0150	.0160	-
LI-7-9S	"	.0165	.0170	.0180	-
AB-7-2L	"	.0276	.0280	.0280	-
AB-7-9L	"	.0295	.0290	.0310	-
KK-7-3S	"	.0150	.0156	.0173	-
JJ-8-6S	72.70	.0153	.0160	.0158	-

TABLE 8

TORQUED TENSION TEST RESULTS

Threads as Received

Bolt Lot	Proof Load kips	Number of Specimens Tested	Load at 1/2 turn kips	Load at 5/8 turn kips	Ultimate Load			Rupture Load, kips	Elongation, inches					Nut Rotation to Rupture revs.
					Mean, kips	Std. Dev. kips	% Direct Tension Ultimate		At Proof Load	At 1/2 Turn	At 5/8 Turn	At Ult. Load	After Rupture	
AC-7-2S	48.50	3	49.1	57.6	61.3	1.36	84.5	47.0	.0122	.0128	.0210	.0512	0.113	1-1/2
AC-7-9S	"	3	52.8	55.1	56.5	0.87	87	36.7	.0165	.0260	.0369	.0614	0.167	1-3/4
BC-8-2S	63.65	3	75.3	77.8	78.5	3.50	86.5	43.3	.0110	.0202	.0308	.0389	0.110	1-1/4
BC-8-11S	"	3	70.2	72.2	72.7	4.49	88	55.3	.0150	.0291	.0304	.0473	0.110	1-1/4
CC-7-12S	48.50	3	51.1	53.6	55.7	0.30	89.5	40.3	.0170	.0227	.0345	.0669	0.160	1-7/8
DC-8-16S	63.65	3	70.8	73.5	74.5	1.50	90	49.7	.0150	.0299	.0430	.0562	0.170	1-3/4
AD-7-2S	55.45	3	48.9	62.8	70.5	1.82	85	58.0	.0147	.0127	.0185	.0376	0.080	1-1/4
AD-7-9S	"	3	60.9	64.8	66.9	2.11	87.5	53.0	.0165	.0209	.0313	.0510	0.120	1-3/8
BD-8-2S	72.70	3	84.5	90.7	90.7	0.58	89	71.7	.0140	.0181	.0280	.0280	0.103	1
BD-8-11S	"	3	72.5	80.5	83.0	7.86	83	58.0	.0165	.0173	.0273	.0441	0.120	1-3/8
CD-7-2L	55.45	3	45.7	50.1	71.9	1.86	87	66.7	.0270	.0219	.0244	.0652	0.110	1-3/8
CD-7-9L	"	4	46.9	55.7	62.6	2.06	84	56.2	.0285	.0240	.0316	.0610	0.105	1-1/4
DD-8-2L	72.70	3	64.0	80.0	90.3	1.15	85.5	70.7	.0260	.0223	.0289	.0498	0.107	1-1/4
DD-8-11L	"	3	67.0	78.8	84.0	2.65	87	59.7	.0280	.0262	.0345	.0537	0.147	1-5/8
ED-7-12S	55.45	4	59.2	64.0	67.6	1.95	87	52.8	.0168	.0183	.0279	.0484	0.145	1-3/8
FD-8-16S	72.70	3	77.8	83.8	88.2	2.36	89	68.8	.0175	.0222	.0298	.0541	0.143	1-3/8
GD-7-12L	55.45	3	32.7	42.6	69.3	0.87	92	58.0	.0265	.0155	.0206	.0725	0.127	1-3/4
HD-8-16L	72.70	3	66.7	81.5	91.2	1.44	91	75.3	.0270	.0250	.0336	.0616	0.173	1-3/4
LI-7-2S*	55.45	5	53.4	59.9	61.1	2.80	80.5	40	.0160	.0162	.0216	.0260	0.075	1-1/4
LI-7-9S*	"	5	50.0	55.4	58.4	3.00	81	34	.0180	.0156	.0206	.0310	0.110	1-5/8
AB-7-2L*	"	6	48.6	57.5	65.4	2.80	89	52	.0280	.0235	.0291	.0530	0.080	1-3/8
AB-7-9L*	"	5	41.1	50.8	61.8	2.18	87	50	.0310	.0219	.0268	.0700	0.114	1-3/4
KK-7-3S	"	10	56.2	60.2	60.4	3.50	77.7	47.5	.0173	.0182	.0276	.0295	0.062	1
JJ-8-6S *	72.70	5	81.0	85.8	87.3	1.26	87.9	64	.0158	.0201	.0311	.0466	0.145	1-1/2

*Snug load was taken as 10 kips for these lots

TABLE 9

TORQUED TENSION TEST RESULTS

Threads Lubricated

Bolt Lot	Proof Load, kips	Number of Specimens Tested	Load at 1/2 turn kips	Ultimate Load			Rupture Load kips	Elongation, inches				Nut Rotation to Rupture revs.
				Mean, kips	Std. Dev. kips	% Direct Tension Ult.		At Proof Load	At 1/2 Turn	At Ult. Load	After Rupture	
AC-7-2S	48.50	3	51.5	62.5	1.13	86	44.3	.0121	.0130	.0555	0.117	1-5/8
AC-7-9S	"	3	52.0	56.8	0.50	87.5	40.3	.0170	.0225	.0583	0.157	1-3/4
BC-8-2S	63.65	3	74.2	76.5	1.80	84	52.0	.0125	.0208	.0371	0.103	1-1/4
BC-8-11S	"	3	67.2	71.5	3.00	86.5	51.3	.0160	.0220	.0518	0.133	1-1/2
CC-7-12S	48.50	3	50.8	55.2	0.53	89	43.0	.0180	.0231	.0628	0.160	1-7/8
DC-8-16S	63.65	3	70.2	73.7	3.34	89	54.7	.0155	.0243	.0608	0.153	1-3/4
AD-7-2S	55.45	3	60.3	78.6	1.46	94.5	59.3	.0135	.0152	.0496	0.127	1-1/2
AD-7-9S	"	3	58.0	65.8	6.25	86	50.3	.0195	.0199	.0537	0.150	1-5/8
BD-8-2S	72.70	3	83.5	91.3	7.37	89.5	73.7	.0140	.0178	.0367	0.100	1-1/8
BD-8-11S	"	3	68.0	78.8	5.80	79	60.3	.0180	.0170	.0401	0.117	1-3/8
CD-7-2L	55.45	3	47.8	76.1	0.93	92	58.0	.0270	.0228	.0627	0.143	1-3/4
CD-7-9L	"	3	46.7	66.6	0.82	89.5	56.3	.0290	.0239	.0630	0.133	1-1/2
DD-8-2L	72.70	3	58.3	99.0	2.78	94	77.0	.0255	.0201	.0603	0.115	1-5/8
DD-8-11L	"	3	69.7	85.0	3.28	88	58.7	.0280	.0269	.0684	0.153	1-3/4
ED-7-12S	55.45	3	61.9	68.5	0.45	88	58.0	.0155	.0192	.0489	0.137	1-1/2
FD-8-16S	72.70	3	61.3	85.5	8.26	86	66.3	.0220	.0164	.0611	0.180	1-7/8
GD-7-12L	55.45	3	36.1	68.1	0.70	90.5	60.3	.0270	.0163	.0651	0.107	1-5/8
HD-8-16L	72.70	3	61.7	90.3	2.08	90	68.0	.0280	.0236	.0869	0.170	1-7/8

TABLE 10

COMBINED TORQUED-DIRECT TENSION TESTS

Bolt Lot	Number of Specimens Tested	Nut Rotation revs.	Ultimate Load	% Direct Tension Ult.
AC-7-9S	3	5/8	63.3	97
AD-7-2S	2	"	85.8	103
AD-7-9S	3	"	74.0	97
CD-7-9L	3	"	75.0	101

TABLE 11

REPEATED TORQUED TENSION TESTS

Bolt Lot	Proof Load, kips	Number of Specimens Tested	Nut Rotation revs.	Mean Load at Specified Nut Rotation, kips				Cycles to Failure
				Cycle 1	Cycle 2	Cycle 3	Cycle 4	
AC-7-9S	48.5	3	3/4	54.7	50.0	-	-	2.9
BC-8-2S	63.65	3	3/4	70.7	-	-	-	1.7
BC-8-11S	"	3	3/4	63.7*	-	-	-	1.8
BC-8-11S	"	3	1/2	64.5	56.2	48.0**	-	4.0
AD-7-9S	55.45	3	3/4	64.5	53.5**	-	-	2.3
CD-7-9L	"	3	3/4	62.8	57.8	-	-	2.8

* Passed Ultimate Load on first Cycle
**Average of 2 remaining bolts

TABLE 12

BOLTS INSTALLED IN STEEL PLATE

Bolt Lot	Number of Specimens Tested	Elong. at 1/2 turn of Nut, inches	Computed Load at 1/2 turn of Nut, kips	% of Load at 1/2 turn from Table 7	Elong. after Rupture, inches	Nut Rotation to Rupture, revs.	Nut Rotation to Rupture from Table 8
BC-8-11S	3	.0392	71.6	102	0.093	1	1-1/4
BD-8-2S	3	.0286	89.5	106	0.070	1	1
BD-8-11S	3	.0386	82.0	113	0.097	1	1-3/8
ED-7-12S	3	.0346	65.5	110	0.117	1-1/8	1-3/8
FD-8-16S	3	.0282	83.0	107	0.183	1-3/4	1-3/8
GD-7-12L	3	.0359	63.0	192	0.137	1-1/2	1-3/4
LI-7-12S	5	.0286	60.5	113	0.096	1-1/4	1-1/4
LI-7-9S	5	.0229	57.3	114	0.100	1-1/2	1-5/8
KK-7-3S	5	.0248	59.5	106	0.060	7/8	1

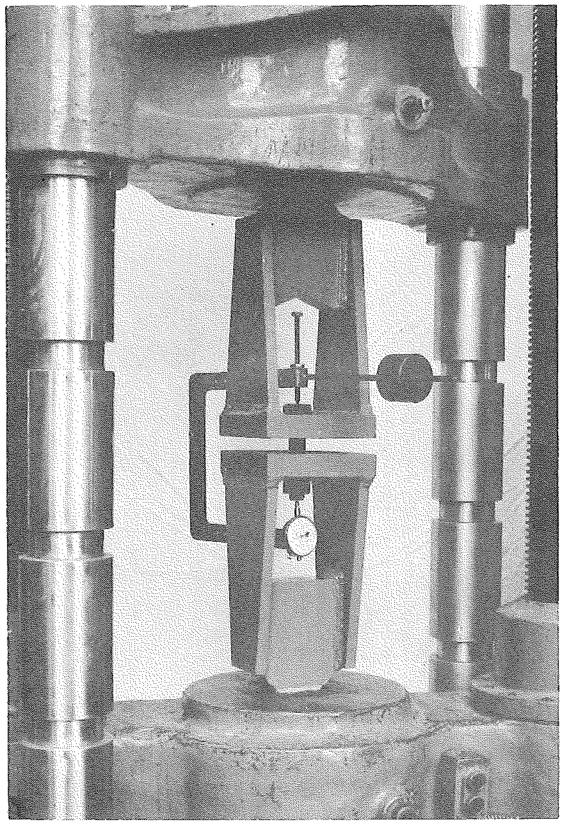


Fig. 1 Direct Tension Test Apparatus

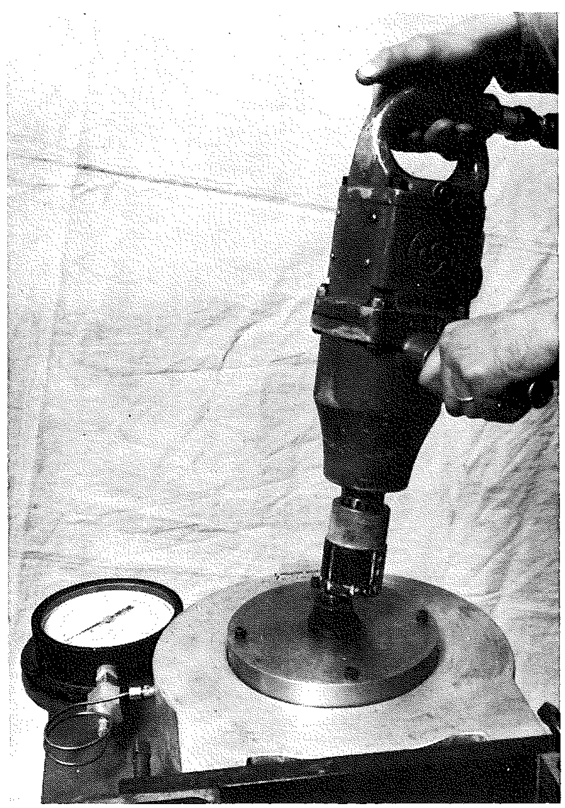


Fig. 2 Large Capacity Bolt Calibrator

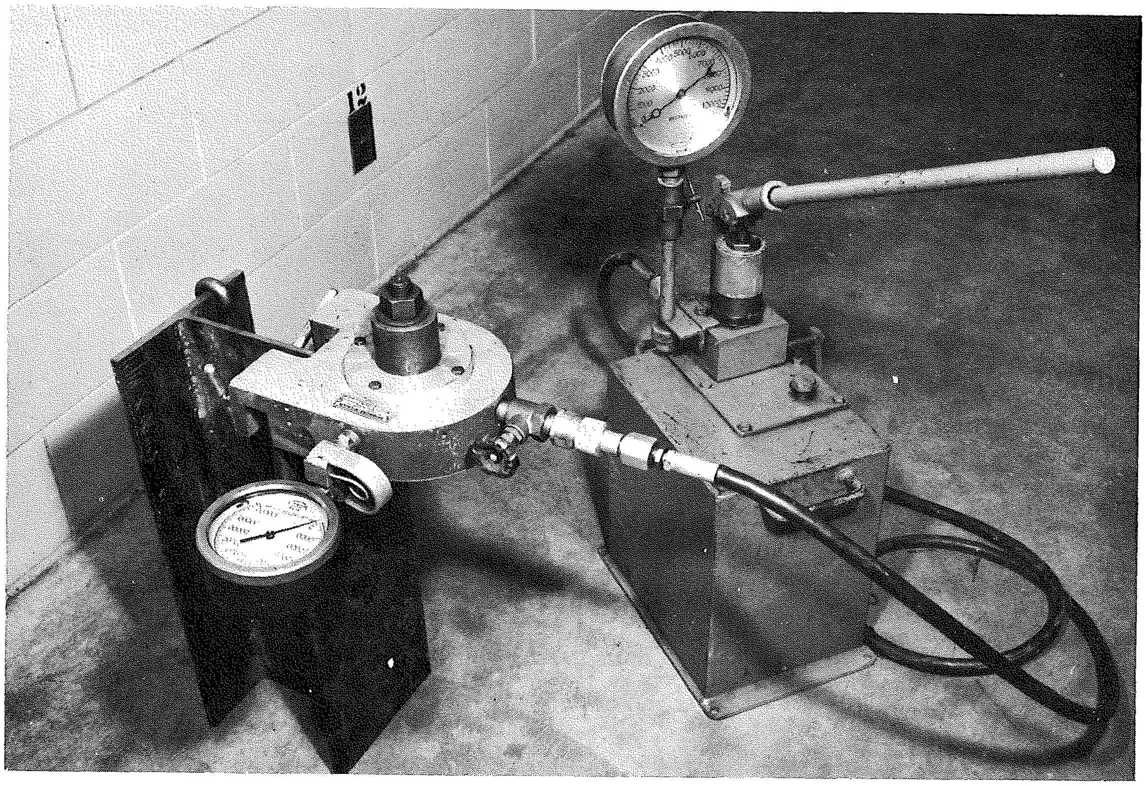


Fig. 3   Bolt Calibrator with Pump

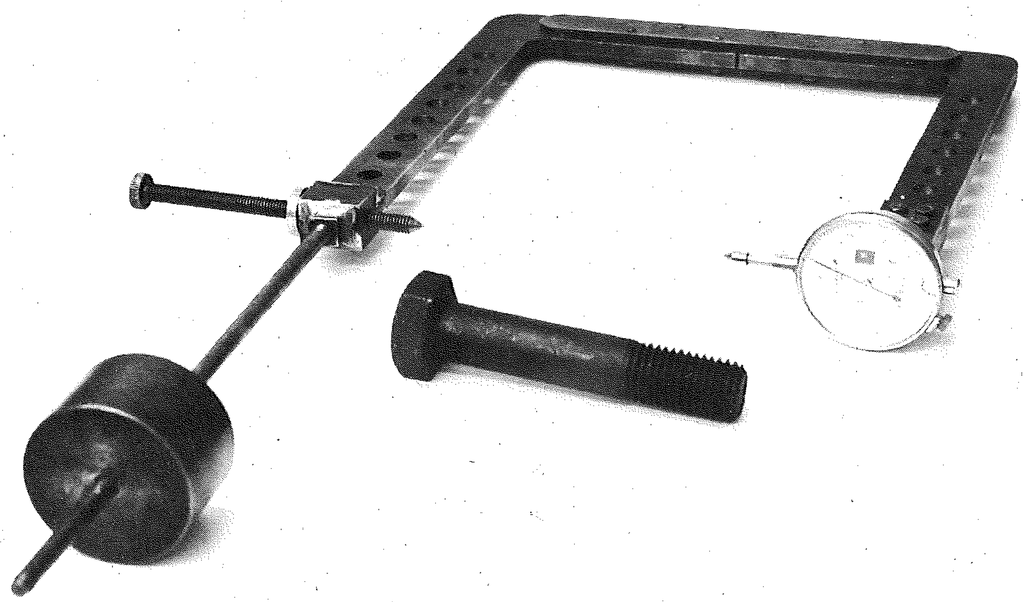


Fig. 4   Extensometer

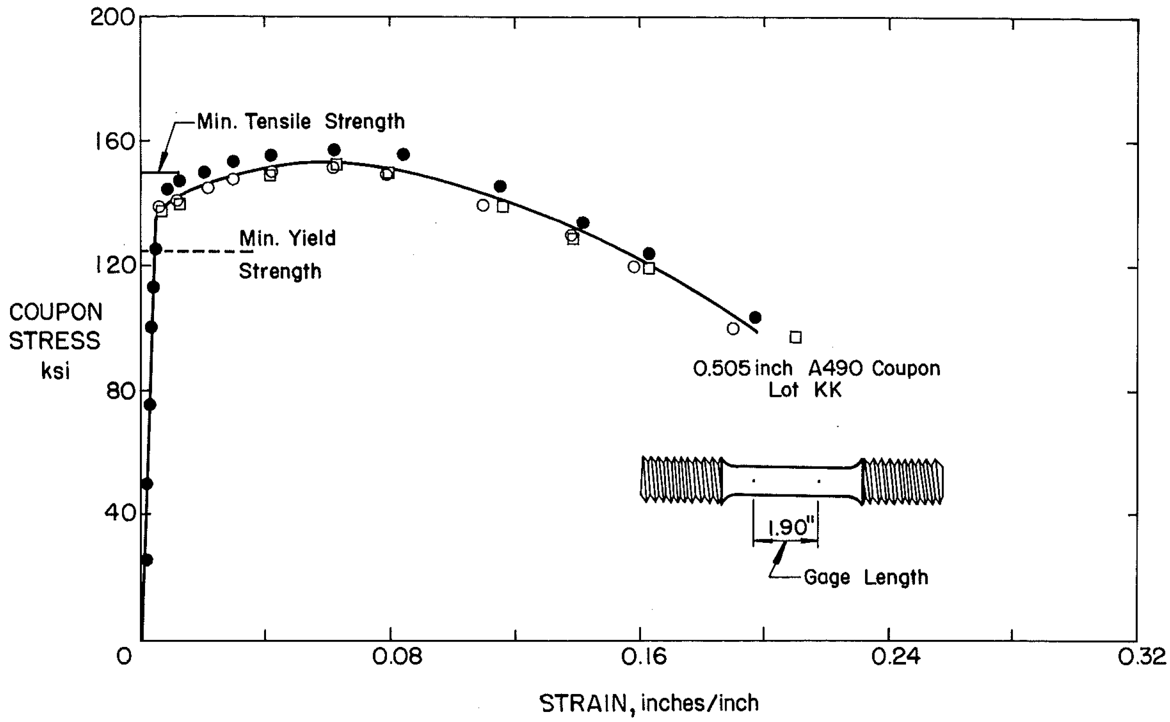


Fig. 5 Coupon Stress-Strain Relationship

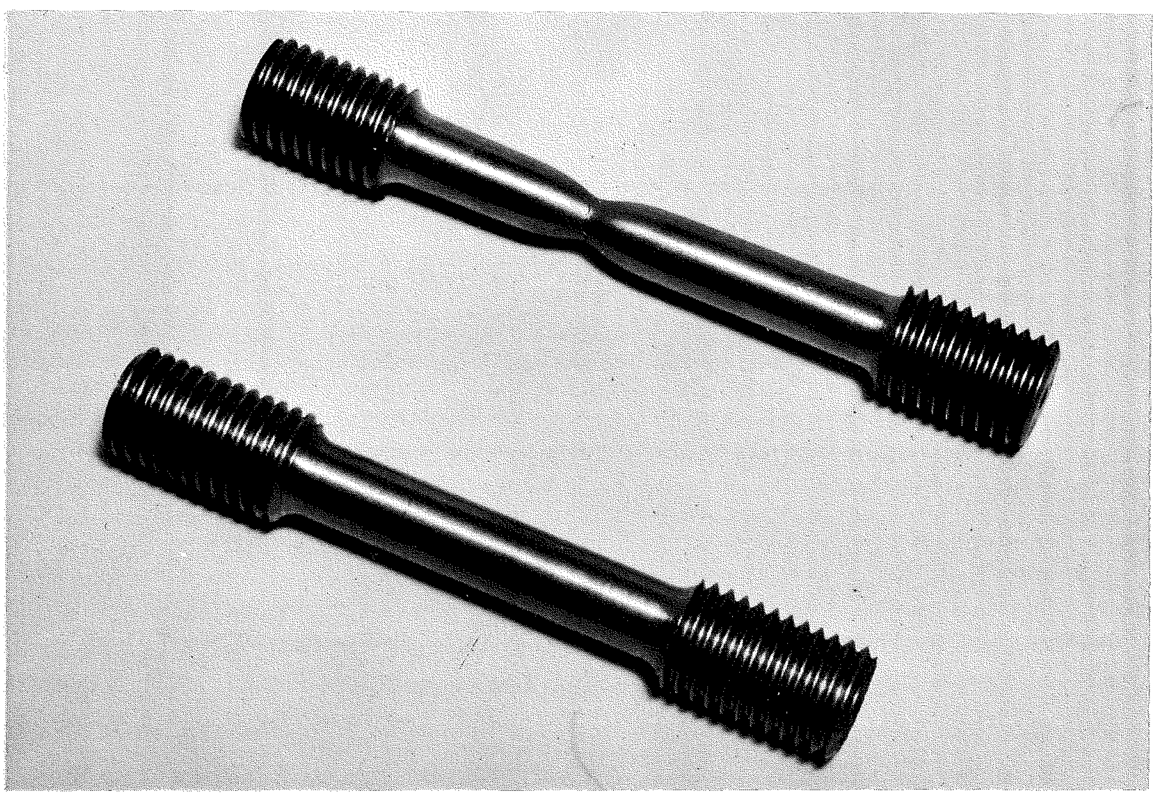


Fig. 6 Coupons Before and After Testing

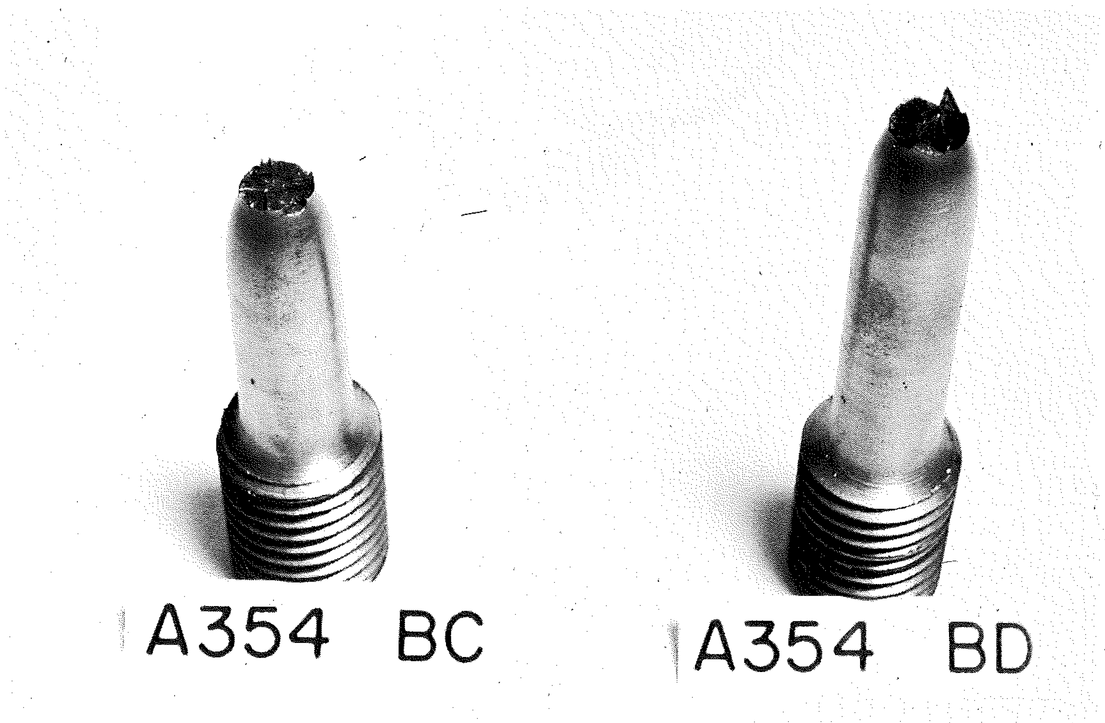


Fig. 7 Comparison of Coupon Fractures

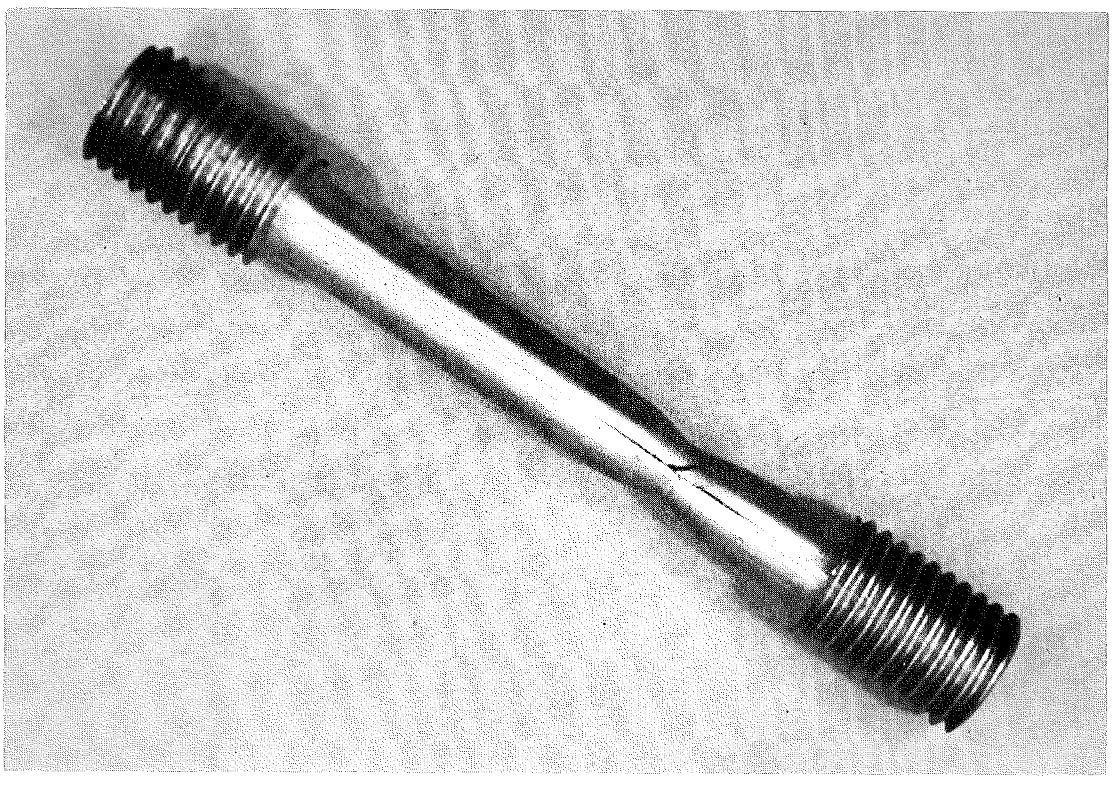


Fig. 8 Longitudinal Fault in Coupon

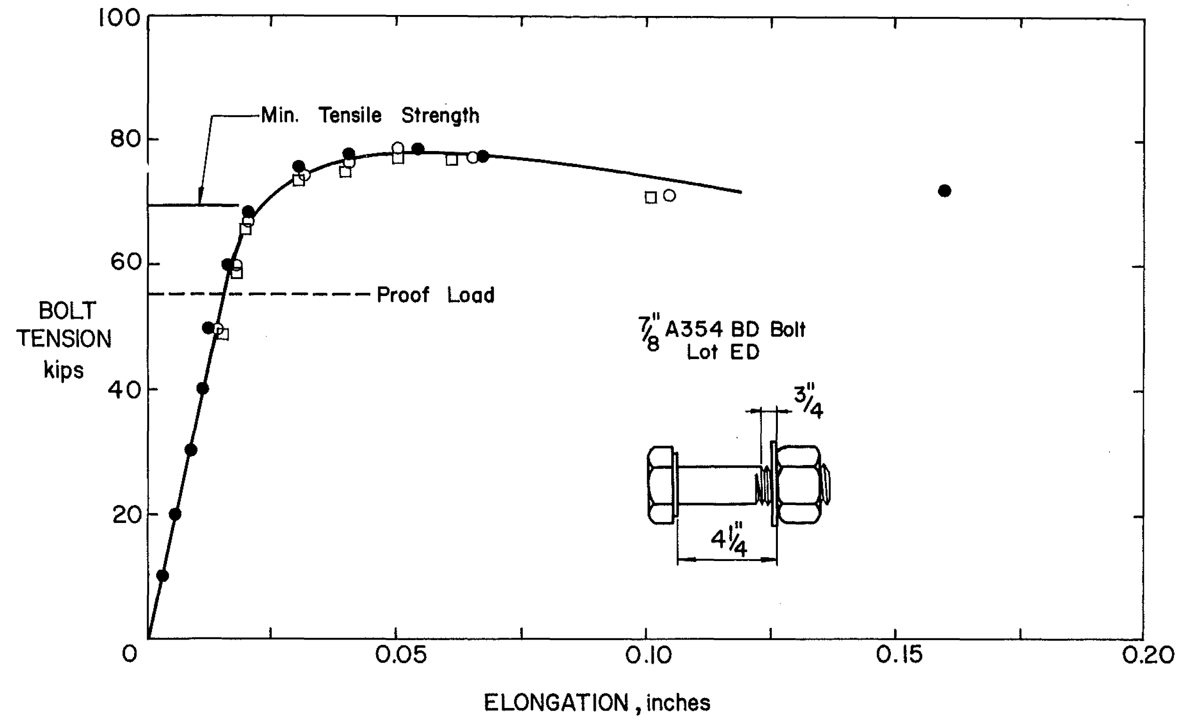


Fig. 9 Load-Elongation Relationship, Direct Tension

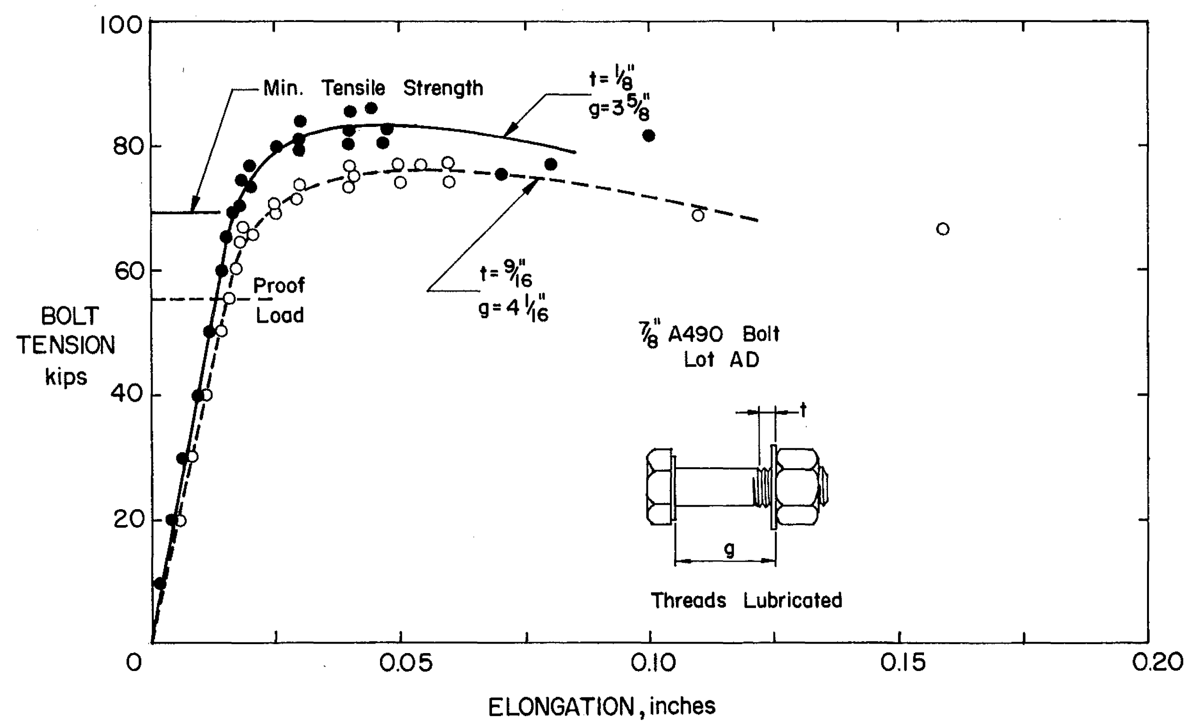
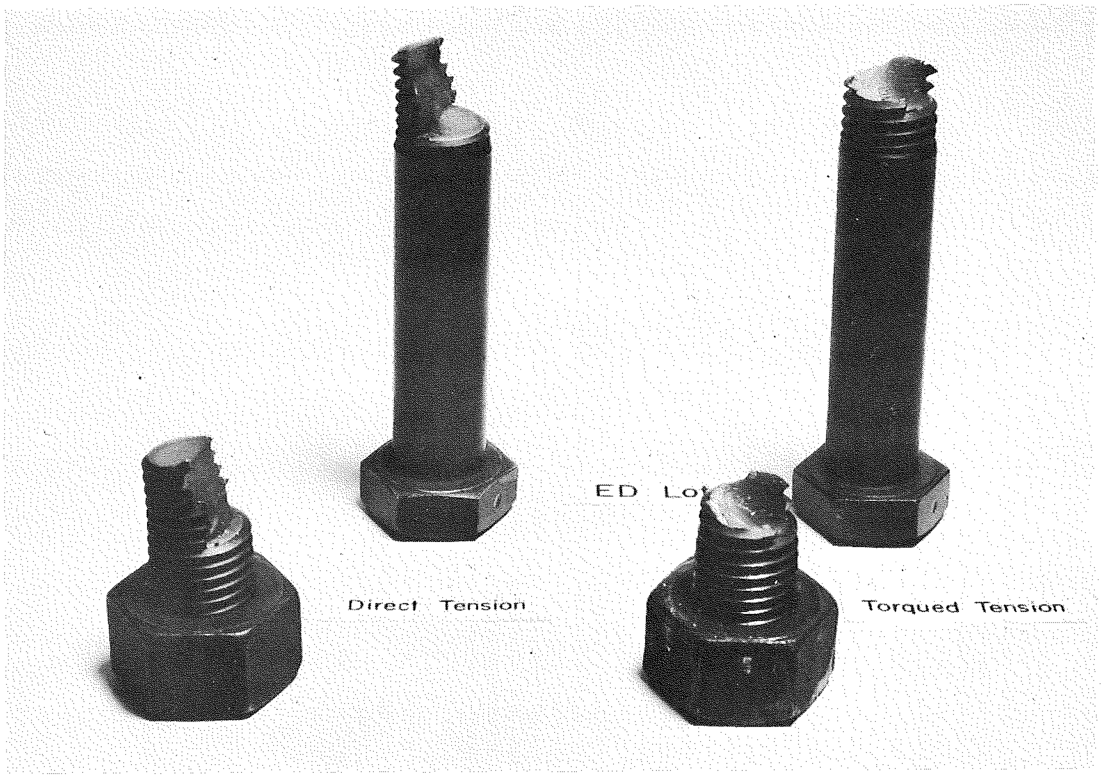
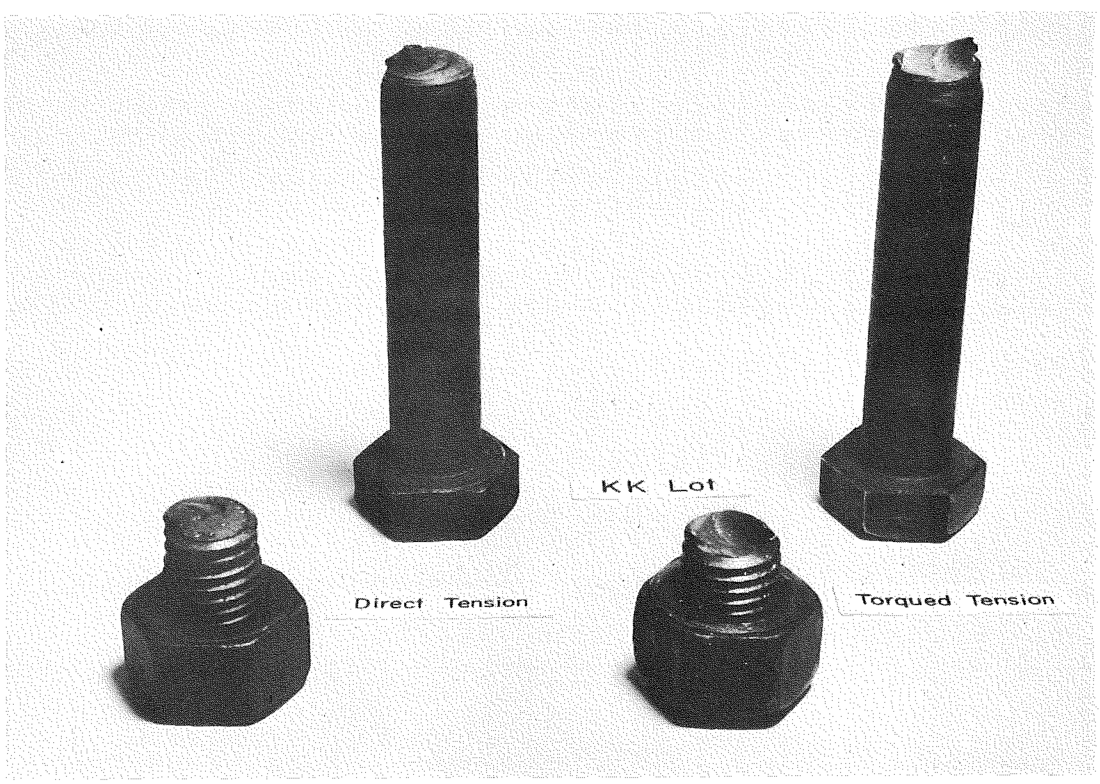


Fig. 10 Effect of Thread Length Under Nut, Direct Tension



a) Long Thread



b) Short Thread

Fig. 11 Bolt Fractures

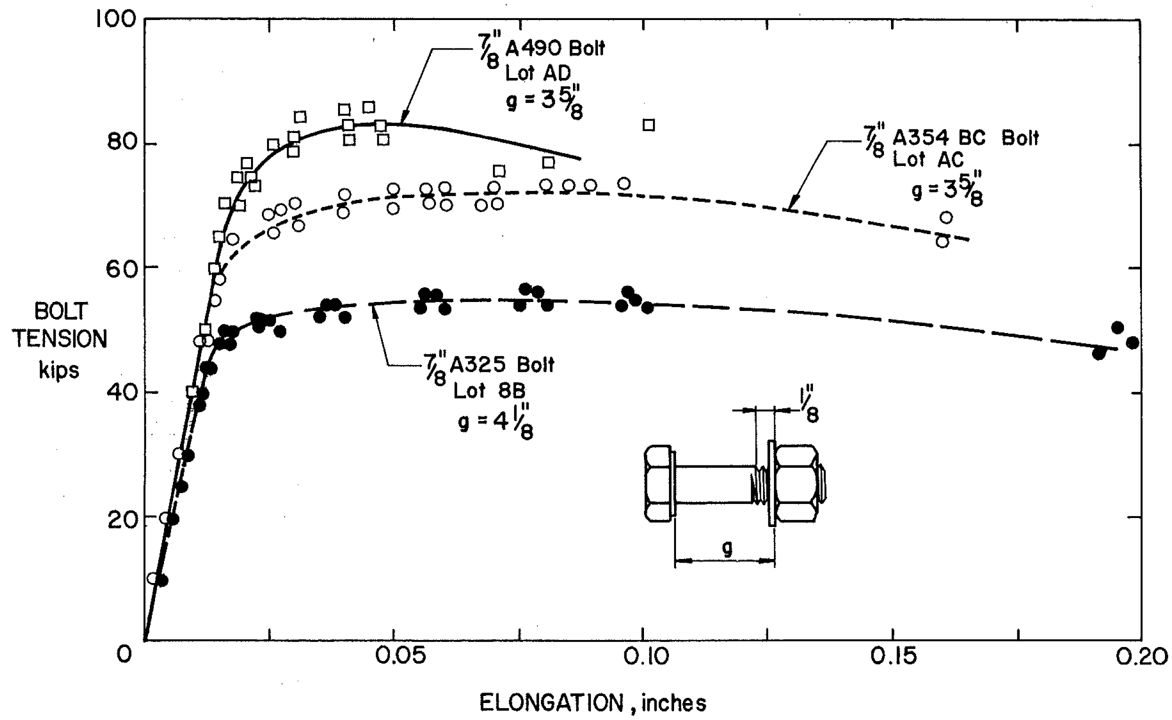


Fig. 12 Comparison of Bolt Types, Direct Tension

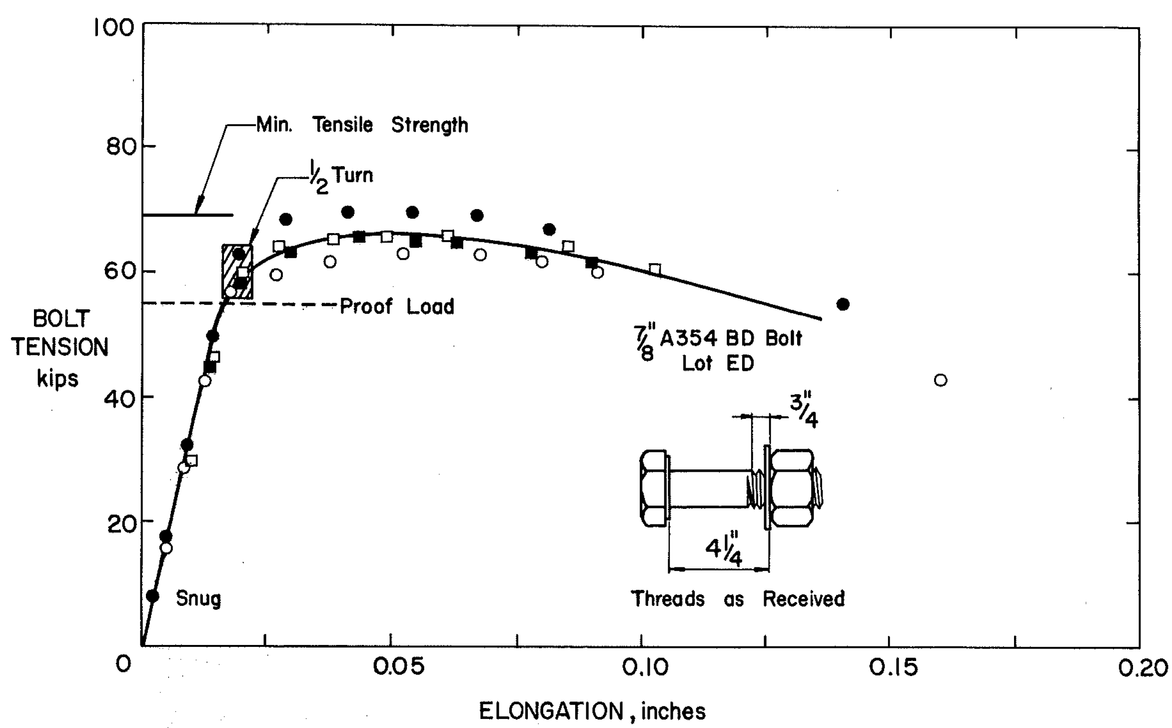


Fig. 13 Load-Elongation Relationship, Torqued Tension

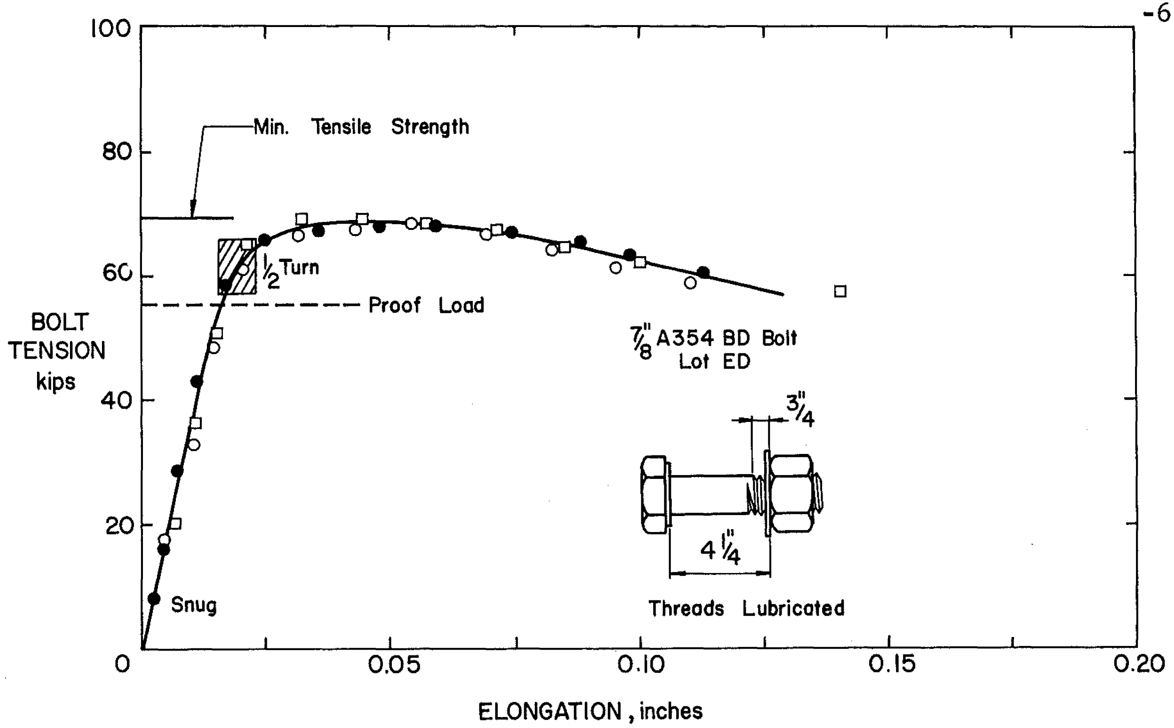


Fig. 14 Load-Elongation Relationship, Torqued Tension

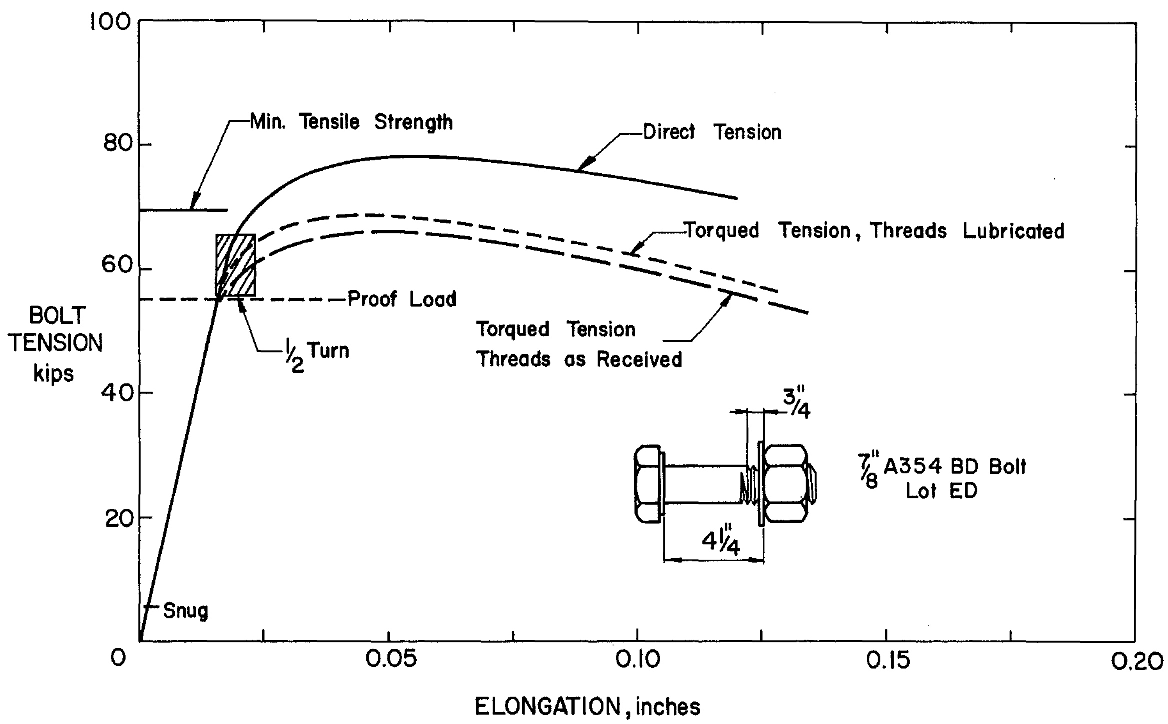


Fig. 15 Comparison of Loading Methods

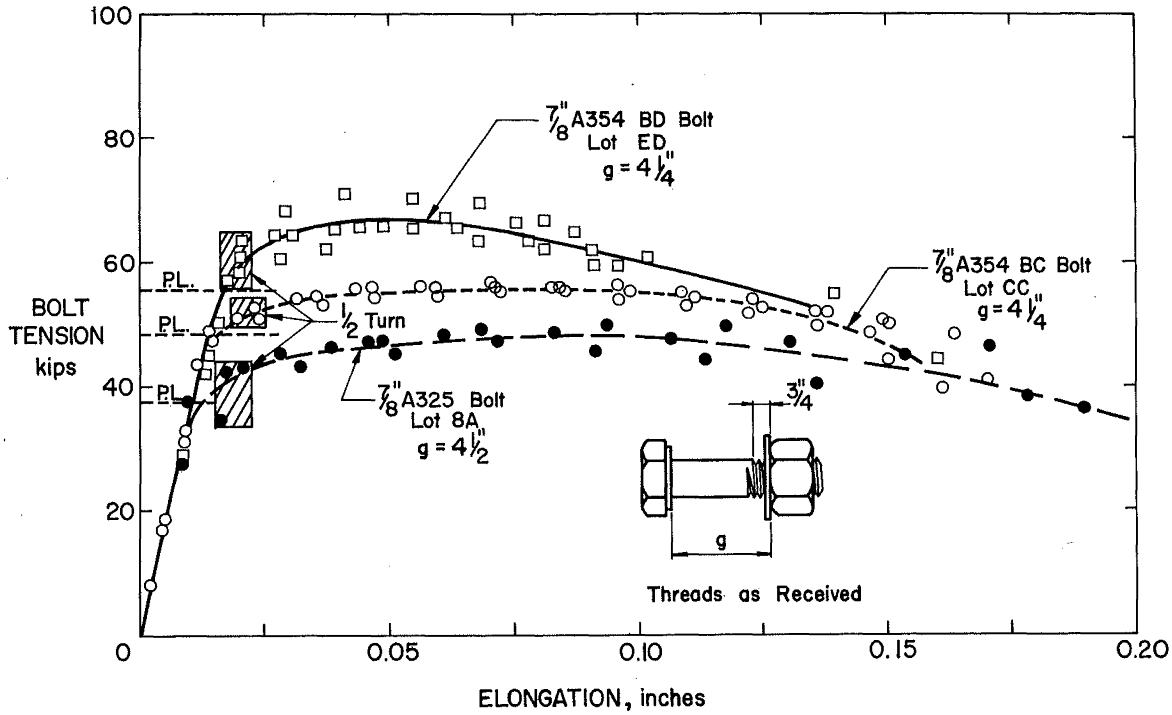


Fig. 16 Comparison of Bolt Types, Torqued Tension

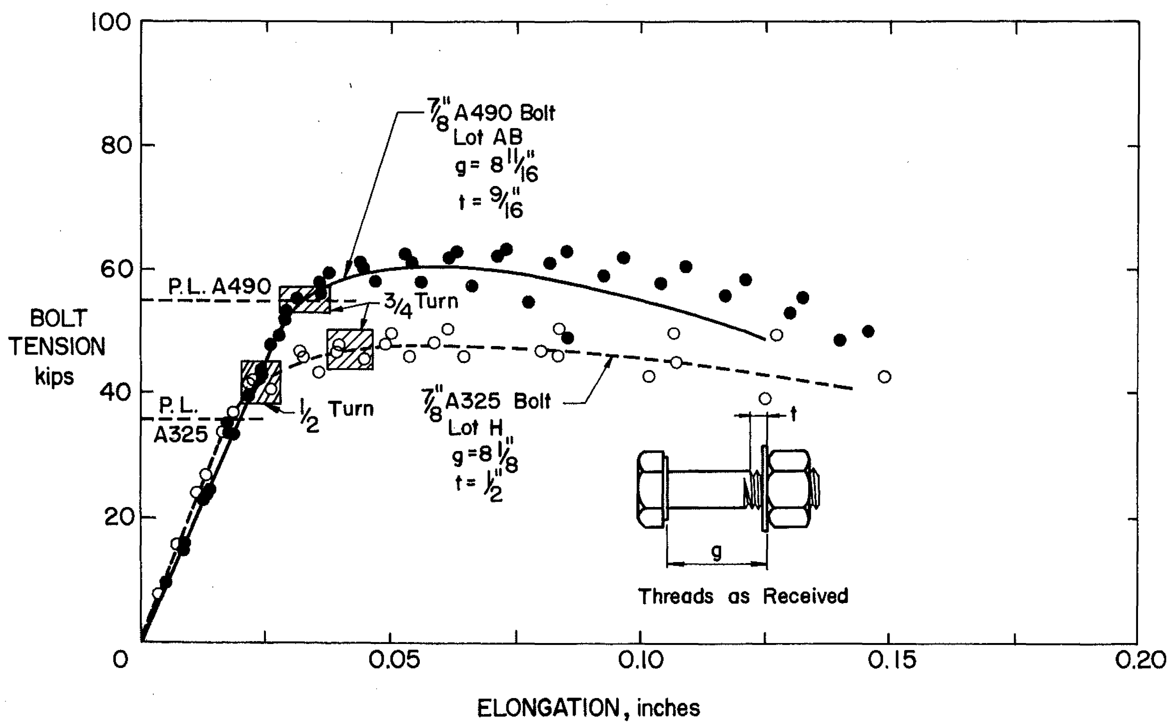


Fig. 17 Long Bolts, A325 vs. A490, Torqued Tension

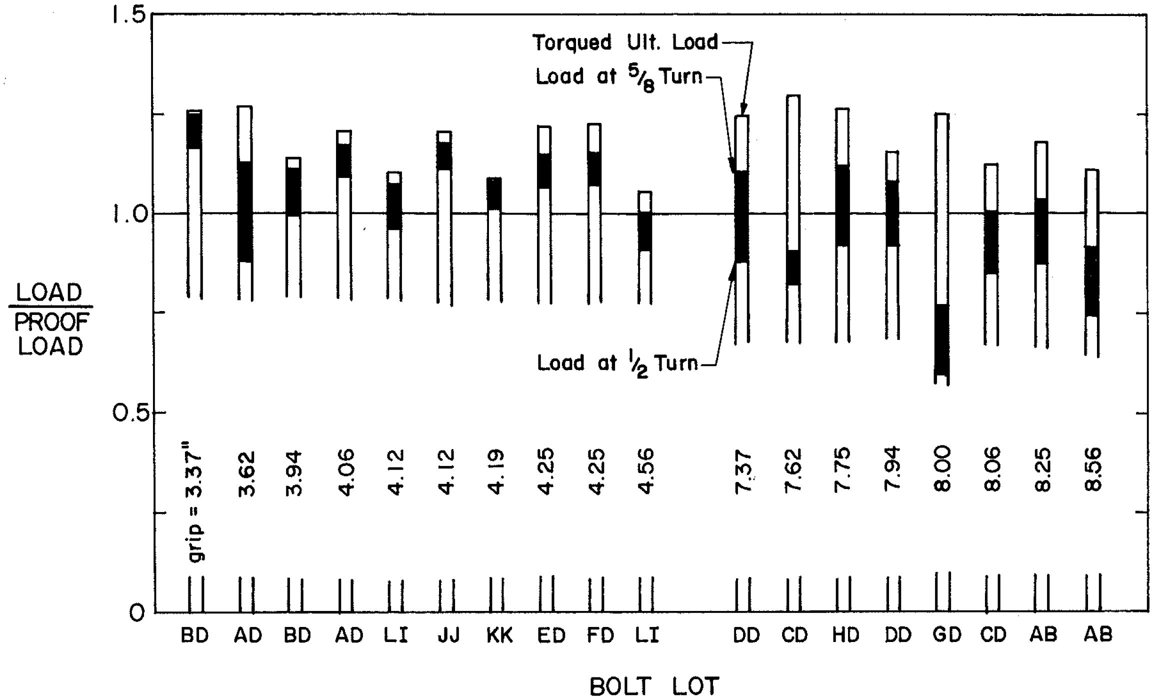


Fig. 18 Load at Specified Nut Rotation

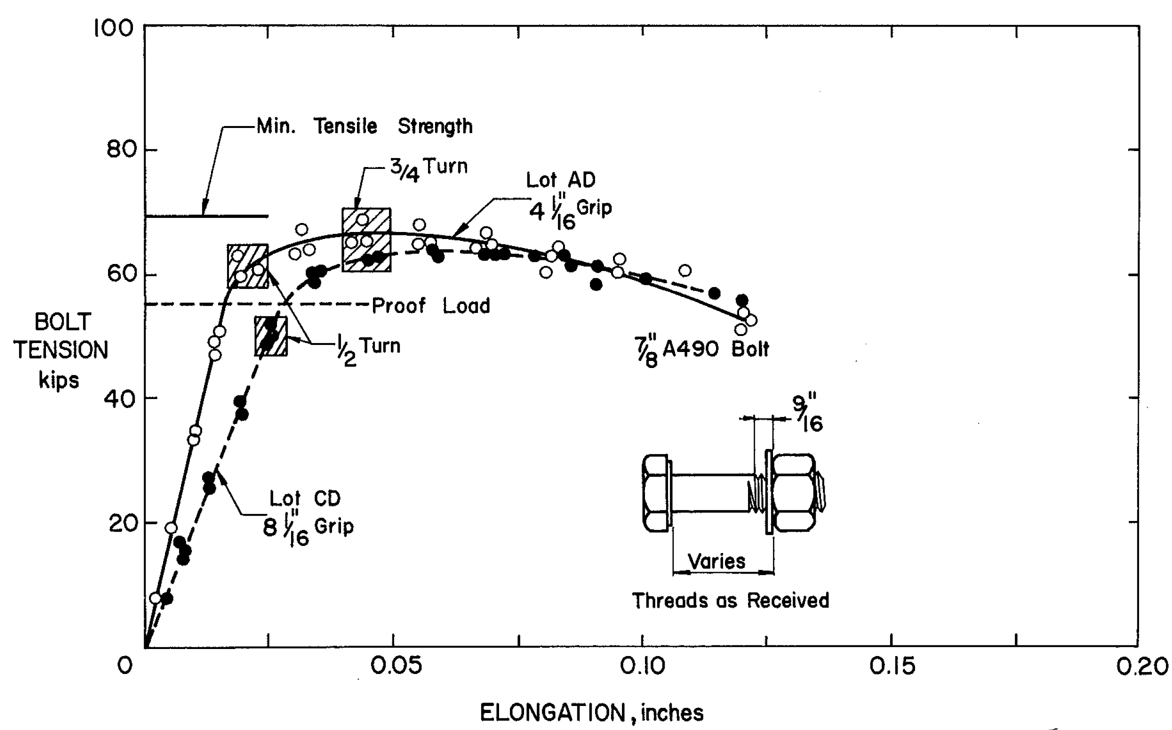


Fig. 19 Effect of Grip Length, Torqued Tension

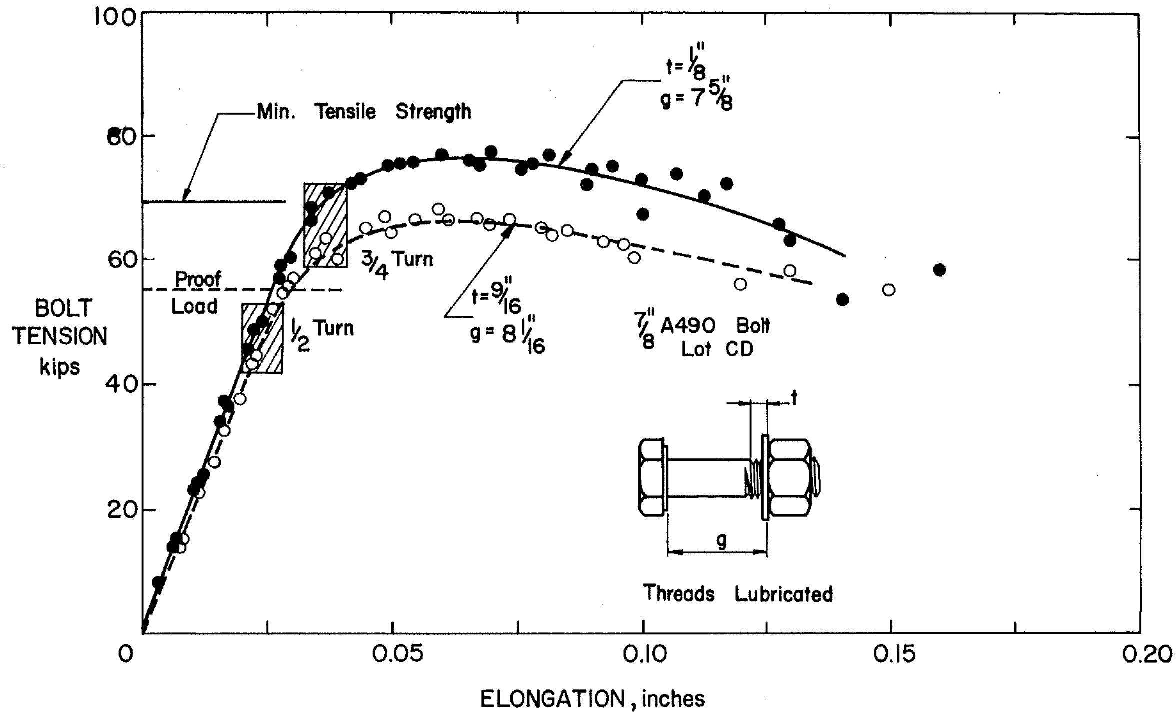


Fig. 20 Effect of Thread Length Under Nut, Torqued Tension

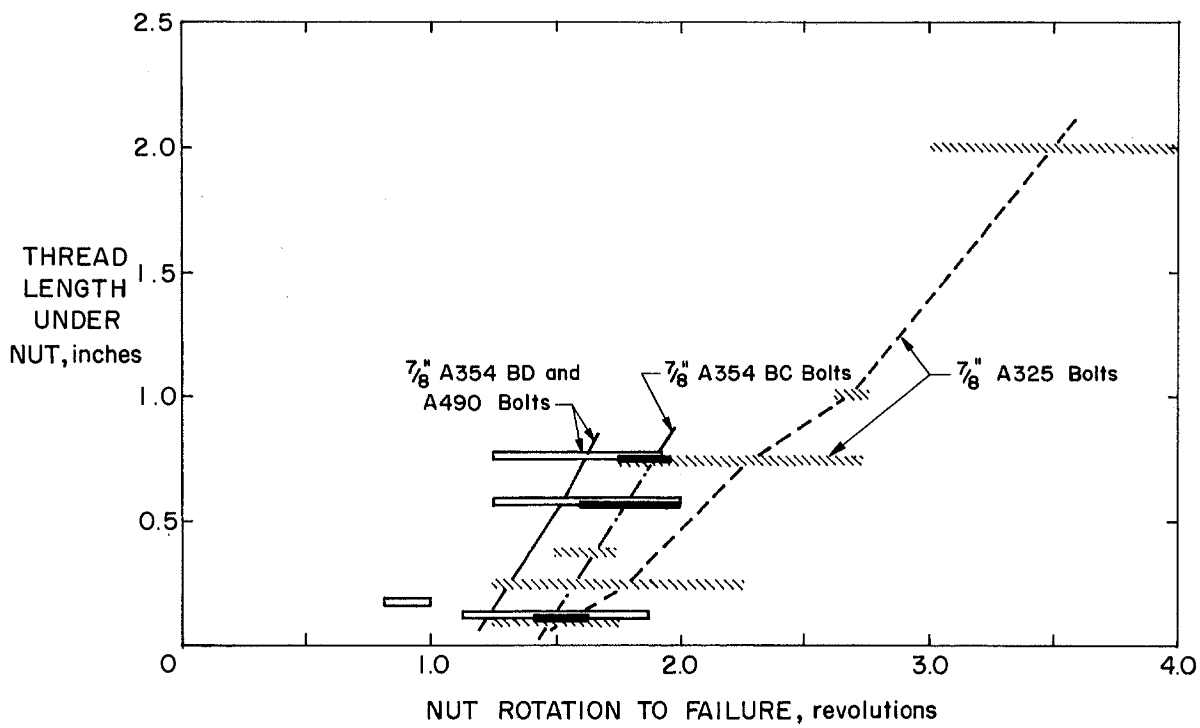


Fig. 21 Effect of Thread Length on Rotation Capacity

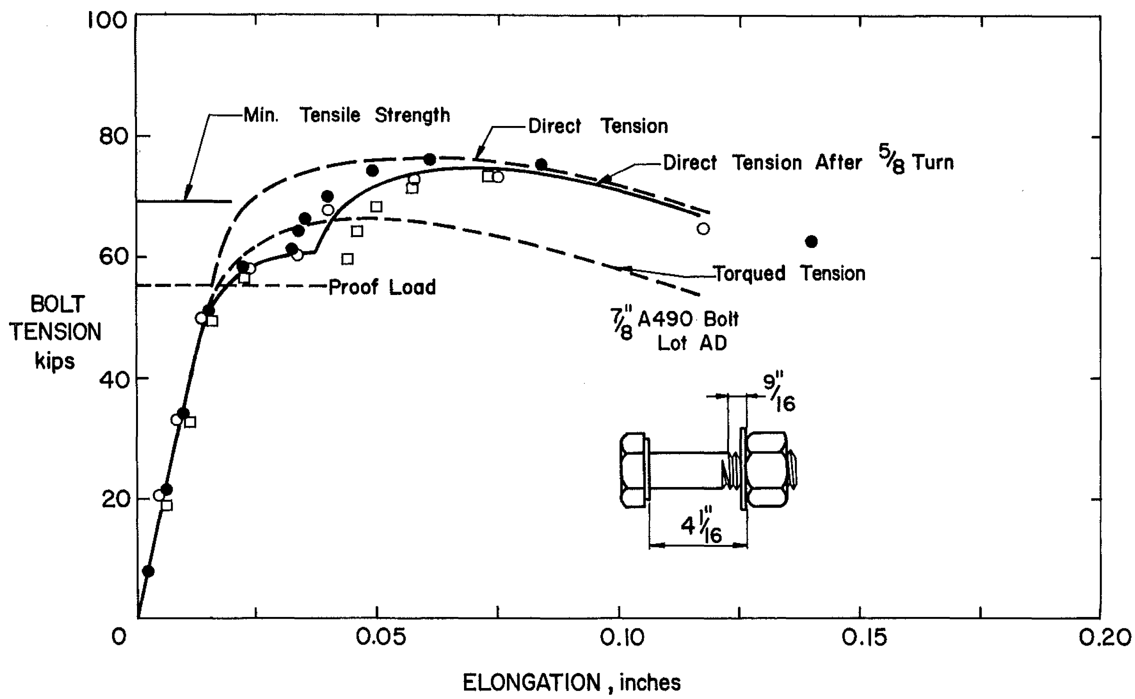


Fig. 22 Reserve Tensile Strength of Torqued Bolts

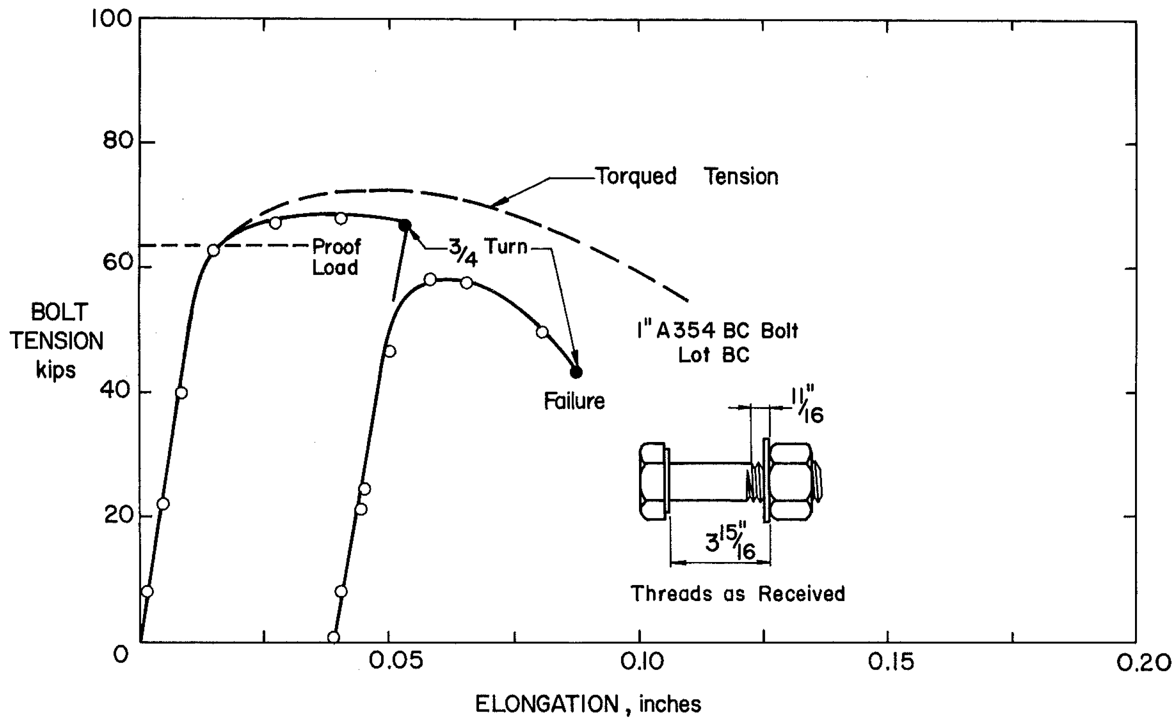


Fig. 23 Repeated Installation of Bolts, 3/4 Turn-of-Nut

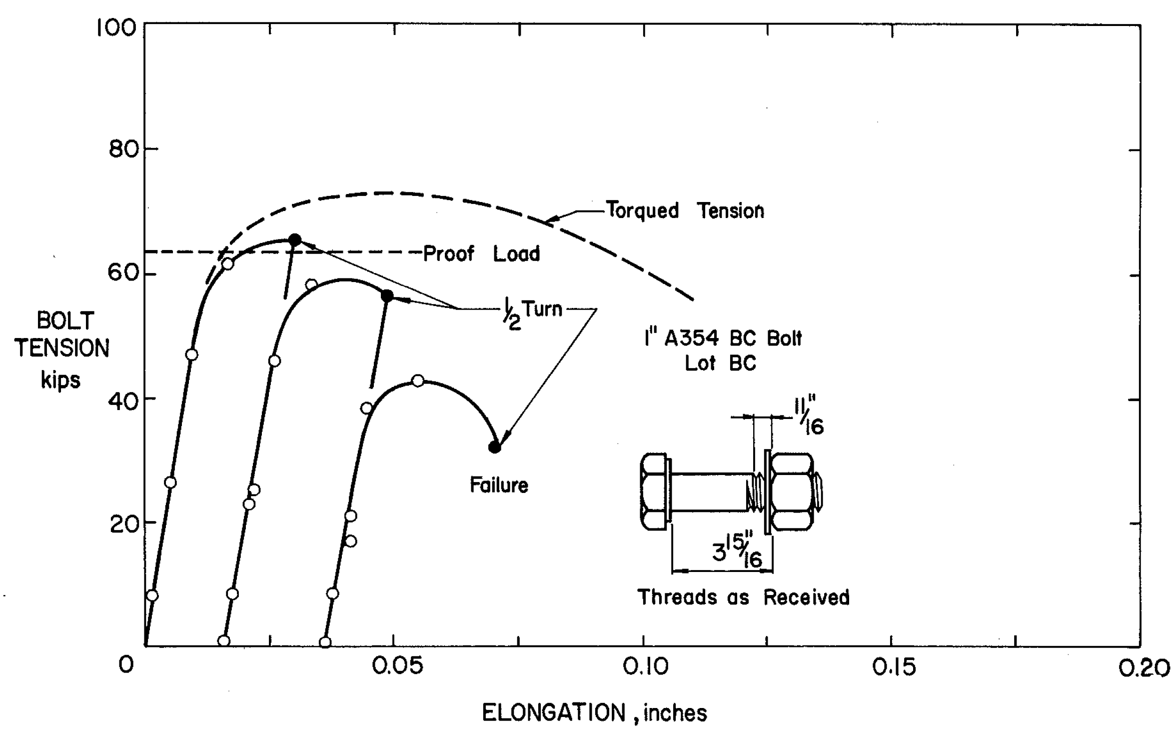


Fig. 24 Repeated Installation of Bolts, ½ Turn-of-Nut

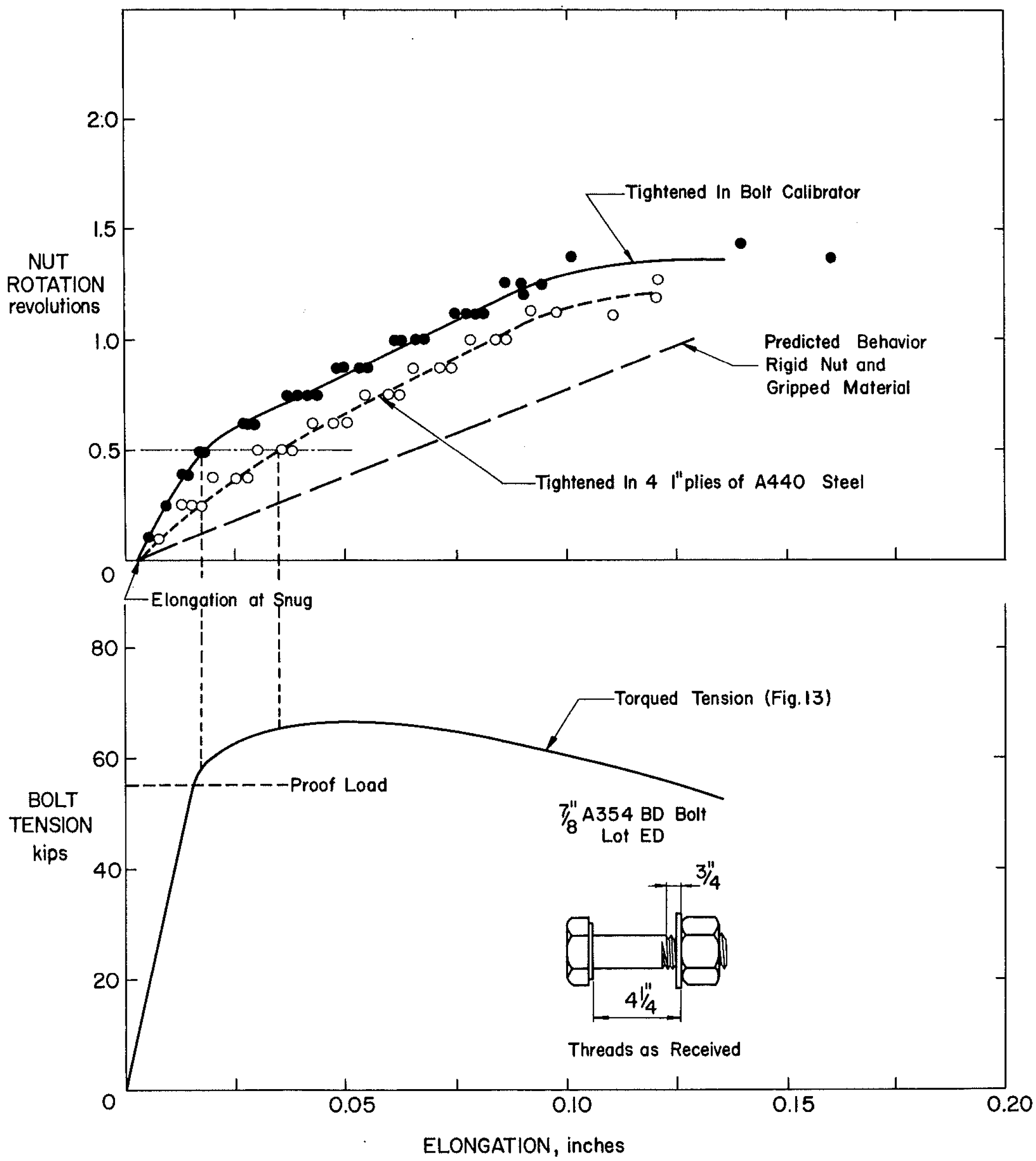


Fig. 25 Bolts Torqued in Steel Plate

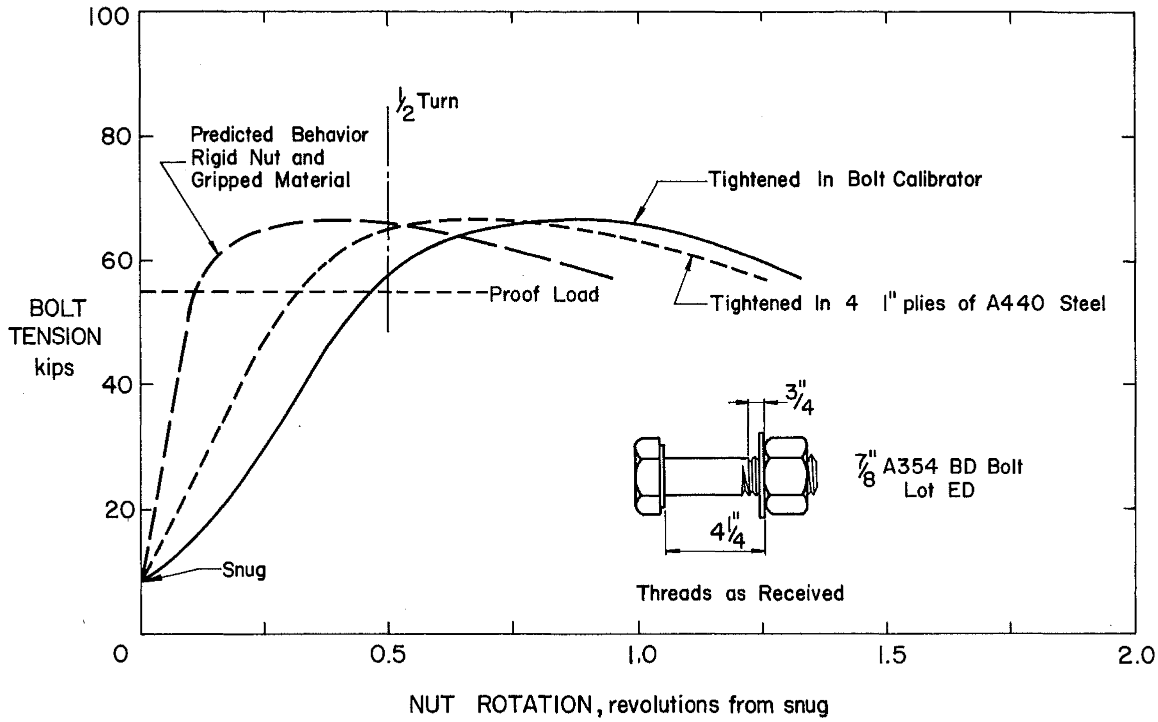


Fig. 26 Tension-Nut Rotation Relationships

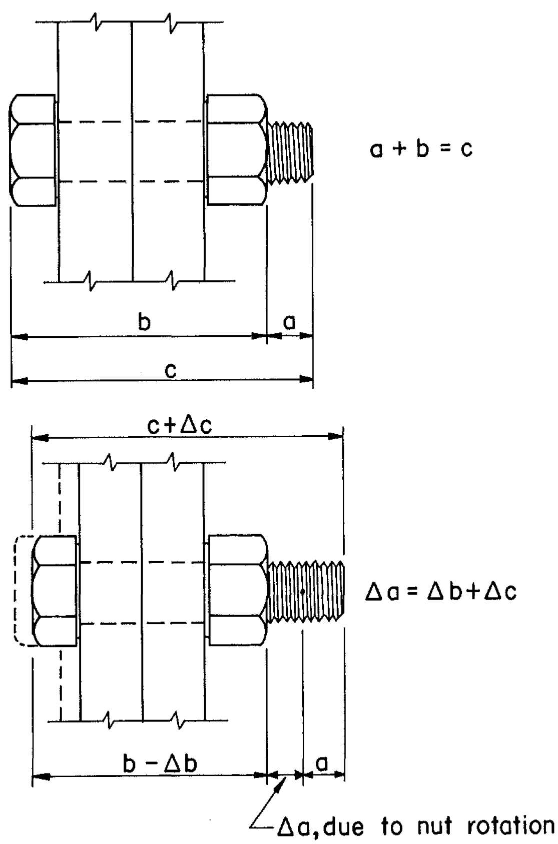


Fig. 27 Deformation of a Bolt Assembly

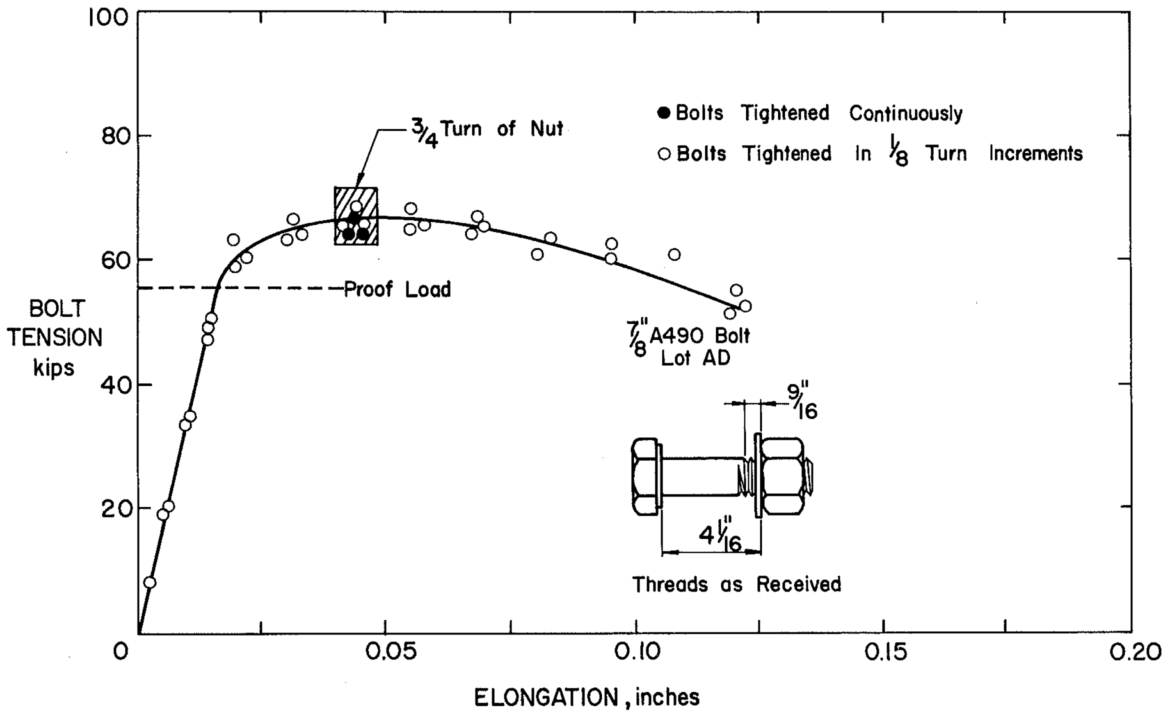


Fig. 28 Continuously Torqued Bolts

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8. VITA

Richard Jay Christopher was born on May 29, 1940 in Oak Park, Illinois, the first child of George W. and Donna Jean Christopher. He attended primary and secondary schools in Peoria, Illinois and graduated from Richwoods Community High School in 1958. He then enrolled at Bradley University in Peoria, receiving his Bachelor of Science Degree in Civil Engineering in 1962. During these undergraduate years he was elected to membership in Phi Eta Sigma, and Sigma Tau and helped to initiate a pilot chapter of Tau Beta Pi which has since been activated as the Illinois Delta chapter.

From 1958 to 1962 he worked part time as a draftsman and structural designer for a local architect. He was married on August 1, 1959 to the former Kathryn Elizabeth Bain and their family now includes two young sons.

In June, 1962, he came to Lehigh as a Research Assistant and one year later was elected secretary of the Fritz Engineering Research Society. He has since become an associate member of ASCE and a student member of the American Concrete Institute.